

2005 - 2009 Annual Report

“Emergence of Adaptive Motor Function through  
Interaction among the Body, Brain and Environment  
- A Constructive Approach to the Understanding of  
Mobiligence - ”

Project Leader: Hajime Asama (The University of Tokyo)



March, 2010

Area No. 454

Under Grant-in-Aid for Scientific Research  
on Priority Area

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# Introduction of the *Mobiligence* Program

## Emergence of Adaptive Motor Function through Interaction among the Body, Brain and Environment - A Constructive Approach to the Understanding of *Mobiligence* -

Hajime Asama  
Director of the *Mobiligence* Program  
The University of Tokyo

### 1. Introduction

The *Mobiligence* program is a five-year program started from 2005[1], which was accepted as a program of Scientific Research on Priority Areas of Grant-in-Aid Scientific Research sponsored by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). Currently, 40 subjects are being carried out (11 subjects for planned research group, 20 subjects for applied research group, and one subject for operation). The first, the second, and the third international symposium on *mobiligence* was held in Dec., 2005[2], July, 2007[3], and Nov., 2009[4] respectively, in which we discussed mainly the research results obtained in the *mobiligence* program and the research plans.

In this report, the outline of the program including the objective and the organization is presented. The concept of *mobiligence*, which can be defined as intelligence for generating adaptive motor function which emerges by mobility, and the approach to understand the mechanisms that generate the adaptive behaviors are explained, and a part of the main research outcome is introduced.

### 2. Program Objective of the *Mobiligence* Program

All the life forms such as humans, animals, and insects, can behave adaptively even in diverse and complex environment in various types of behaviors, such as locomotive behaviors in the form of swimming, flying, and walking, manipulation behaviors such as reaching, capturing, and grasping by using hands and arms, social behaviors to the other subjects, etc. The intelligent sensory-motor functions to generate adaptive behaviors are considered most essential and indispensable for them to survive.

It is known that such function for adaptive behaviors is disturbed in patients with neurological disorders. Parkinson disease is a typical example of such disorders on adaptive motor function, and autism or depression can also be considered as a disorder on social adaptive function. Recently, due to aging or environmental change of society, the population of people who are suffering from these diseases is growing rapidly, and it has become urgent to cope with this problem. However, the mechanisms of generating such adaptive behaviors are not thoroughly known yet. With this background, the objective of the program is set to understand the mechanism that generates the adaptive behaviors.

### 3. Concept of *Mobiligence*

Such an adaptive function is considered to emerge by the active mobility of the cognitive subject. In the subject is in the stationary state, there is not so much interaction among body, brain, and environment. However, once the subject starts to move, the signals to move the body are transmitted from the brain to the body. As the result of the motion of the body, the physical interaction between the body and environment are made, and due to the interaction, the information from environment is input to the brain directly or fed back to the brain via the body as somatosensory signals. Namely, the motion of the subject accelerates the interaction among body, brain, and environment, which is considered essential for the subject to behave adaptively. Based on the consideration, we built up a working hypothesis that the adaptive function emerge from the interaction among the body, brain and environment, which requires actions or motions of the subject, and defined *mobiligence* as intelligence for generating adaptive motor function which emerges by mobility.

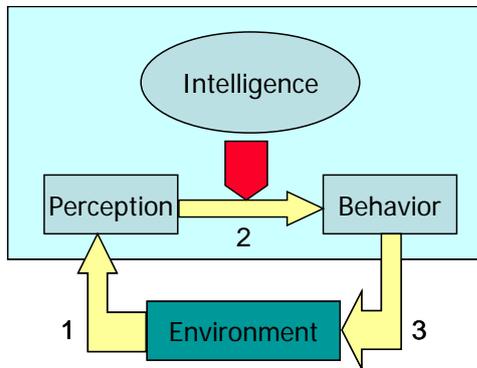
The information which can be acquired by mobility can be listed as follows:

1. Diverse information by changing location of the subject
2. Dynamical information by motion
3. Experience accumulated in the subject

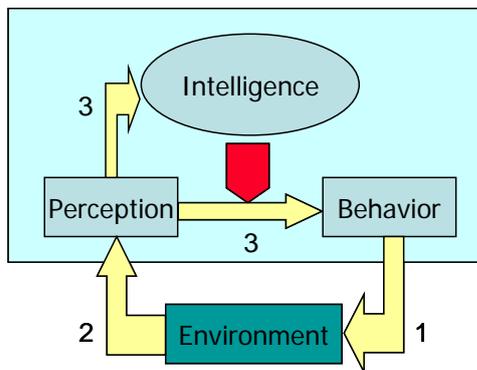
There is difference in the concept of the conventional robotics and *mobiligence*, which are compared in fig. 1.

In the conventional robotics, which discusses intelligence for mobility, the first step is perception and cognition. The subject recognizes the environment based on the information perceived by sensors, then plans the motions by applying knowledge which should be implemented in advance, and behaves by controlling the actuators, namely, moves the body, which causes the interaction to the environment, as shown in fig. 1-(a). On the other hand, in the concept of *mobiligence* which investigates intelligence emerged by mobility, the first step is behavior as shown in fig. 1-(b). The perception is initiated by the behavior. As a result of the behavior, rich information can be acquired by the interaction between the body and the environment, and input to the brain. The information can be accumulated in the brain, and utilized concurrently to generate adaptive behaviors in real time. The combination of the two concepts derives the tight and continuous loop between cognition and

behavior or among body, brain, and environment, which is considered quite important to understand the intelligence of living systems that behave adaptively or to design the intelligence of the autonomous artificial robots.



(a) Concept of conventional robotics



(b) Concept of Mobiligence

Fig. 1. Comparison of the concepts of conventional robotics and *mobiligence*

#### 4. Collaborative Research of Biology and Engineering

It is typical to use animal experiments in the conventional biological research. By this analytical approach, large amount of knowledge and findings have been obtained so far, such as the structure and function of various neural networks, neural transmitters/modulators, etc. However, there is also limitation in this conventional analytical approach based on animal experiments. The animal experiments are usually made with animals in the fixed conditions, and they can reveal only the simple brain function in a stationary state. For the *mobiligence* research, where it is required to investigate the complex function which emerges through interaction among brain, body, and environment in a dynamic state, the mechanisms that generate adaptive behaviors are hardly able to be elucidated only by the conventional analytical approach. To overcome the problem, a new approach was introduced to tackle this problem in the *mobiligence*

program. Based on the knowledge of biological research, such as neurophysiology, neuroethology, clinical medicine, cognitive science, microbiology, physiological models are to be derived. To these biological models, dynamic system modeling technology is applied to derive biological system models, which can be implemented on simulators or actual robot systems. By constructing the adaptive function on the simulators or actual robots based on the models, we can verify the models, evaluate the effects of the various parameters, and introduce new hypotheses to the biological scientists. In the *mobiligence* program, this approach is called a constructive approach by collaborative research of biology and engineering.

In the *mobiligence* program, three methodologies for collaborative research of biology and engineering have been proposed and in practice so far:

##### A. System Biomechanics

By neurophysiological research, we can derive models for nervous systems. On the other hand, by engineering and anthropological research, musculoskeletal models can be derived. By integrating the nervous system models and musculoskeletal models, dynamic system models can be introduced, and can be implemented on simulators or actual robots. As the results of experiments using the simulators or actual robots, we can verify the models or hypotheses, produce new possible hypotheses on the mechanisms which generates the adaptive behaviors, and feed them back to the biological scientists, or provide robotic scientists with design principle to realize adaptive artificial systems. This methodology for collaborative research is shown in figure 2-(a).

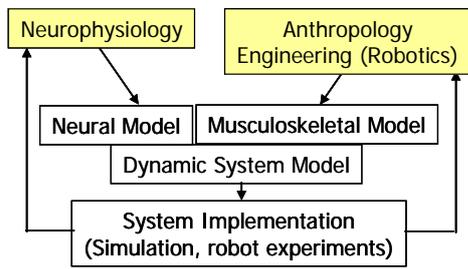
##### B. Synthetic Neuroethology

From neurophysiological research, enormous independent pieces of physiological knowledge are acquired in diverse levels from chemical reaction to cellular and behavioral (individual or social) level. Multiple pieces of the knowledge in multi-levels can be synthesized by technologies in robotics or engineering to derive dynamic system models, which represent the hypotheses of the mechanisms that generate adaptive behaviors. The behavior or performance of the models which should be implemented on simulators or actual robots can be compared with the behavior or performance of the actual living systems, and the models or hypotheses can be verified in ethological manner. This methodology for collaborative research is shown in figure 2-(b).

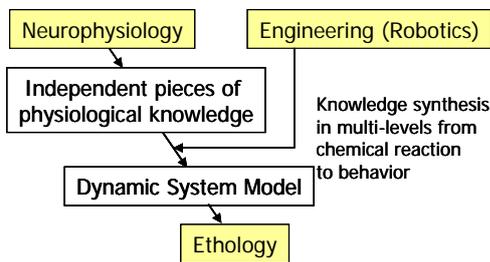
##### C. Brain-Machine Integrated System

Biology can provide us with biological body components, such as brains, limbs, organs etc. Engineering or robotics can provide us with mechanical body parts, such as sensor devices, actuators, processors, etc. By integrate these body parts, we can construct brain-machine integrated systems, which can also be called *cyborg*. By analyzing the behavior and function of the integrated system, we can investigate the function of the biological

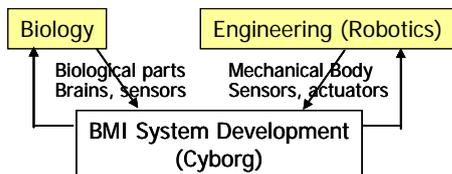
components or systems, and can provide robotics scientists with the methodologies to realize artificial systems that can behave adaptively. This methodology for collaborative research is shown in figure 2-(c).



(a) System Biomechanics



(b) Synthetic Neuroethology



(c) Brain-Machine Integrated System

Fig. 2. Methodologies for collaborative research of biology and engineering

## 5. Research Subjects and Groups

In the *mobiligence* program, we focused on the following three aspects to investigate the mechanisms that generate adaptive behaviors, and organized three research groups for each aspect:

### Group A (Adaptation to the environmental change)

Investigation of mechanism to generate the information adaptively based on cognition of the environmental change

### Group B (Physical Adaptation)

Investigation of mechanism to control the motion of the body adaptively according to the environment

### Group C (Social Adaptation)

Investigation of mechanism to select the behaviors adaptively to the other subjects and the society

The researchers in these three groups conduct their respective research on specific subjects, such as

cognition, learning, motion generation, and body control, focusing on specific life forms, such as humans, animals, and insects in individual level and social level. However, another important target of this program is to clarify the universal and common principle underlying the mechanism of *mobiligence*, and establish the design principle for adaptive systems. We organized the fourth group to understand the common principle:

### Group D (Common Principle)

Investigation of common principle on dynamics in generating adaptive behaviors

## 6. Recent Research Outcome

In the *mobiligence* program, many collaborative research subjects have been initiated, and various valuable research outcome have been obtained so far by the intensive specific research in the group A, B, and C. In parallel to the specific research, some common structures and features have been extracted as the common principle on the structural dynamics or information creation of the mechanisms for adaptation. Followings are a part of the recent research outcome:

In the research of group A, which focuses on cognition to the environmental change, adaptation to dynamic environments in reaching movements as shown in Fig. 3 has been investigated by Ito, et. al[5]. Two types of force fields, namely velocity-dependent force field for internal model adaptation and divergent force field for impedance adaptation, have tested, in which the subject should learn to reach the targets. It was proved that the subjects can learn to generate the optimal hand force patterns in both cases, and can adapt even when that force field was changed in the middle of the motion. As a result of the experiments, it can be assumed that the impedance and internal-model controls can be programmed in a feedforward manner in adaptation to the contexts of dynamic environments. This function is called anticipatory adaptation. Yano, et. al. investigated real time adaptation mechanisms on a feedforward structure, especially mechanisms on generating real time constraints as *Minashi* (abductive) information, taking an example of olfactory computation in slug brain[6]. As a result of experiments, it was found that the initial signals to move the body, which is considered to correspond to

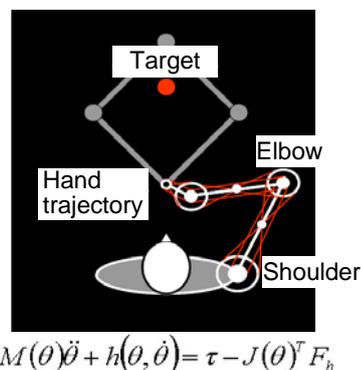


Fig. 3. Reaching behavior

emotional behavior, precedes about 40-60[msec] to the memory accessing signal flow, which is considered to correspond to interpretation of the perceived information.

In the research of group B, which focuses on physical adaptation, namely adaptation in the individual level, emergence and control in adaptive locomotion under changing environment has been investigated by system biomechanics approach, namely systematic approach based on neural and musculoskeletal models. Takakusaki, et. al. investigated function of basal ganglia, cerebral cortex, brainstem, spinal cord, thalamus, limbic system, and cerebellum on locomotion, and discovered a detail structure on the signal flow in the neural networks[7]. Especially, Nakajima, et. al. investigated how cortical motor areas (M1, SMA, PMd) in primates contribute to the gait control by using Japanese (Macaque) monkey[8]. As a result of experiments on recording the firing pattern of cortical neurons during locomotion of macaque monkeys on moving treadmill, it was found that the discharge frequency drastically increased when the monkey converted its locomotor pattern from quadrupedal to bipedal. A block diagram on the locomotion was derived as a physiological model for locomotion, where it was also indicated that the postural control system is activated earlier than the movement control system, and sends feedforward signals to movement control system. On the other hand, Tsuchiya, Ogihara, et. al. developed a musculoskeletal model of Japanese monkey based on anatomical data and CT data by anthropological and engineering approaches[9], which is shown in fig. 4. It is expected to integrate the physiological model and the musculoskeletal model to enable simulation on dynamic locomotion of Japanese monkey by constructive approach for further investigation in near future.

In the research of group C, which focuses on social adaptation, namely adaptation in the social (multi-agent) level, cognition of other agents and selection of adaptive behaviors to other agents or society have been investigated by synthetic neuroethology approach. Aonuma, et. al. focused on fighting behaviors between male crickets as shown in fig. 5. As a result of

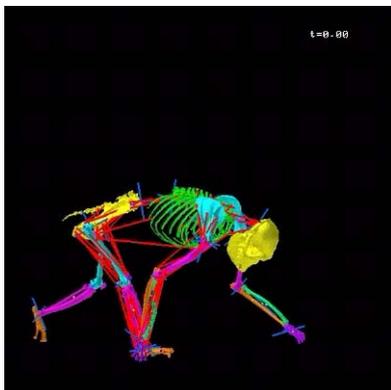


Fig. 4. Musculoskeletal model of Japanese monkey

experimental investigation, new physiological knowledge were obtained such that aggressiveness increases by inhibition of NO/cGMP cascade, OA level in the brain decreases by NO and fighting behavior, and the decrease level depends on the results of fights (win or lose)[10]. Fujiki, Asama, et. al. implemented a mathematical model of the neural mechanism by reaction diffusion equations[11], and Ashikaga and Ota, et. al. implemented a mathematical model of interaction between male crickets by finite automaton[12]. By integrating both models, the behavior selection of male cricket can be simulated from chemical reaction level in the brain to the social interaction level. As a result of simulation results, it was suggested that the different types of the society emerge depending on the density, namely the number of individuals per unit area. Figure 6 is the simulation results on aggressiveness of male crickets depending on the density. The graph shows that all the individuals become aggressive in low density (large field size) condition, while only small number of individuals become aggressive in high density (small field size) condition. It is pointed out in the ethological research that this simulation results fits the behaviors of actual male crickets very well, and from these consideration, the models we derived are proved to be reasonable.

In the research of group C, Kanzaki, et. al. have investigated the adaptive brain function of silk moth by brain-machine integrated system approach[13]. A mobile robot integrated with insect brain, which is shown in fig. 7 has been developed, where the robot can be controlled



Fig. 5. Fighting behavior of male crickets

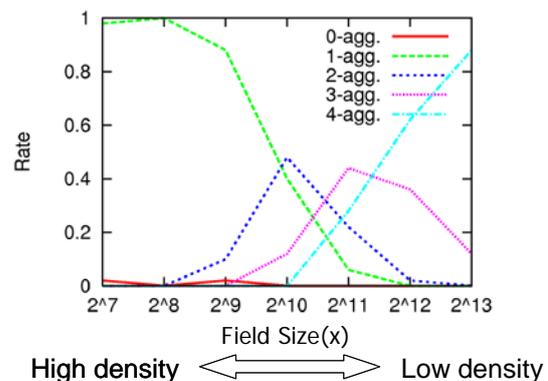


Fig. 6. Simulation results on aggressiveness depending on density

by the embedded insect brain signals. As a result of pheromone source localization experiments with this robot, it was found that the silk moth brain can successfully control the robot body and localize the pheromone source even if the control gain of the right wheel and the left wheel were differentiated. This result verified the plasticity of the silk moth brain. By changing body dynamics, control gain or other parameters of the body, it is expected to investigate the adaptive function of the silk moth brain and neural systems more in detail.

In the research of group D, which focuses on common principle, balance dynamics in mechanical properties and information processing in control has been investigated from the viewpoint of physical constraints, because it is considered that the balance between mechanical embodiment and neural control system is considered very important for realization of adaptive function. The main concern of this group is what kind of balance mechanisms exist in living systems, and how this should be designed in autonomous artificial systems. Osuka, et. al. have focused on adaptive function in passive dynamic walking, and discovered a stabilization mechanism by implicit feedback structure in body dynamics[14]. Ishiguro, et. al. have developed a modular robot system “Slimebot” based on collective behavioral approach as mimesis of slime mould (amoeba), which is shown in fig. 8[15]. The robot system employs a fully decentralized control by exploiting embodied coupled nonlinear oscillators, and passivity by s spontaneous inter-modular connectivity control mechanism. As a result of actual robot experiments, it was discovered that a certain passivity can significantly increases its adaptiveness.

From the research outcome obtained so far in the *mobiligence* program, there found a common characteristic in the mechanisms that generate adaptive behaviors as shown in fig. 9. The perceived sensory information is dimensionally compressed in environment cognition. However, the information which can be obtained is not always sufficient to generate motion. In such situation, *Minashi* (abductive) information is generated in real time, which is equivalent to constraints for control of redundant degrees of freedom in the physical body. The motion is not always generated or switched in a reactive manner (such as impedance adaptation). The internal models learned and formed in the brain through experience are quite essential to generate adaptive behaviors effectively according to the context. The motion generation complexity depends much on the embodiment. If the body is well organized, the active mechanism to control the body can be simplified.

## 7. Expected Impact of the *Mobiligence* Program

By the *mobiligence* program, various types of mechanisms that generate adaptive behaviors in various living systems, such as humans, animals, and insects, are expected to be elucidated as well as common principle. Although the main contribution will be brought to biological field, huge impacts to other fields are expected as well. To the medical field, the results of our research

will contribute to the discovery of a method to improve motor impairment and develop rehabilitation systems. To the engineering field, the results of our research will contribute to the derivation of the design principles of artificial intelligence systems. By the *mobiligence* program, the new research discipline is expected to be explored, and a new research organization that integrates biology and engineering is expected to be established, where new programs or curriculums are implemented to foster young engineering scientists and biologists to conduct collaborative and interdisciplinary research between biological and engineering research, respectively.

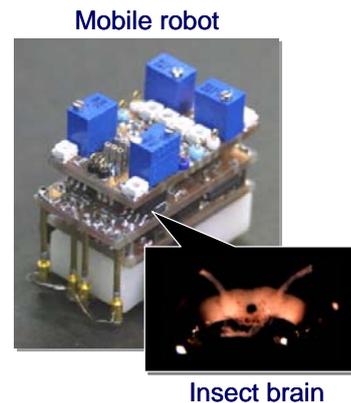
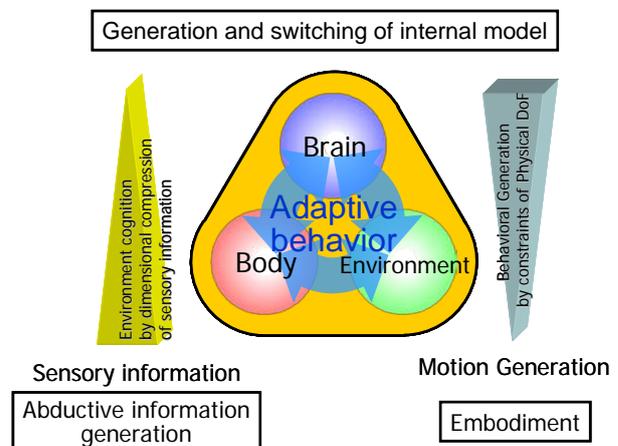


Fig. 7. Mobile robot integrated with silk moth brain



Fig. 8. Modular robot system “Slimebot”



Junior Academy of the *mobiligence* program was established, and tutorials, workshops, and seminars have been carried out for the young researchers in *mobiligence* program. The academy is now working on editing the terminology related to the *mobiligence* research.

## 8. Conclusion

The *mobiligence* program was introduced, which started from 2005 in Japan as a five-year program of Scientific Research on Priority Areas of Grant-in-Aid Scientific Research sponsored by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). The concept of *mobiligence* was explained, which can be defined as intelligence for generating adaptive motor function which emerges by mobility. The objective of the program and the constructive approach by collaborative research of biology and engineering for the *mobiligence* research were mentioned as well as the subjects and organization of the program. Finally, a part of the current research outcome was introduced.

The outline of the program including the objective and the organization was presented. The concept of *mobiligence*, which can be defined as intelligence for generating adaptive motor function which emerges by mobility, and the approach to understand the mechanisms that generate the adaptive behaviors were explained. A part of the recent research outcome was introduced.

Detail and other research outcome was presented in AMAM '08 (Fourth International Symposium on Adaptive Motion of Animals and Machines), in the workshop of IROS '08 (2008 IEEE/RSJ International Conference on Intelligent Robots and Systems), DARS '08 (2008 International Symposium on Distributed Autonomous Robotic Systems), and will be presented in Mobiligence '09 (Third International Symposium on Mobiligence), which will be held in Awaji, Japan, in Nov., 2009.

## Acknowledgment

The concept of Mobiligence and the organization of the Mobiligence program were established through the discussion with Prof. Kazuo Tsuchiya (Doshisha Univ.), Prof. Koji Ito (Tokyo Inst. of Tech.), Prof. Masafumi Yano (Tohoku Univ.), Prof. Kaoru Takakusaki (Asahikawa Medical Col.), Prof. Ryohei Kanzaki (The Univ. of Tokyo), Prof. Jun Ota (The Univ. of Tokyo), Akio Ishiguro (Tohoku Univ.), Hitoshi Aonuma (Hokkaido Univ.), Koichi Osuka (Kobe Univ.), and the other planned research group members. I thank all these members for their valuable contributions. I thank also all the reviewers of the mobiligence program for valuable comments on program organization and research directions, who are Prof. Sten Grillner (Karolinska Inst.), Prof. Avis H. Cohen (Univ. of Maryland), Prof. Rolf Pfeifer (Univ. of Zurich), Prof. Shigemi Mori (National Inst. for Physiological Sci.), Prof. Ryoji Suzuki (Kanazawa Inst. of Tech.), and Prof. Shinzo Kitamura (Kobe Univ.).

## References

- [1] [http://www.arai.pe.u-tokyo.ac.jp/mobiligence/index\\_e.html](http://www.arai.pe.u-tokyo.ac.jp/mobiligence/index_e.html)
- [2] Proceedings of 1st international symposium on mobiligence, Sapporo, Japan, Dec. 2005.
- [3] Proceedings of 2nd international symposium on mobiligence, Awaji, Japan, July 2007.
- [4] Proceedings of 3rd international symposium on mobiligence, Awaji, Japan, Nov. 2009.
- [5] K. Ito, M. Doi, T. Kondo: "Feed-Forward Adaptation to a Varying Dynamic Environment During Reaching Movements", *Journal of Robotics and Mechatronics*, vol. 19, no. 4, pp. 474-481, 2007.
- [6] Y. Makino, H. Makinae, T. Obara, H. Miura and M. Yano: "Observations of Olfactory Information Flows within Brain of the Terrestrial Slug, *Inciralia fruhstorferi*", *Proc. of 2006 Int. Joint Conf. on Neural Networks*, pp. 7605-7612, 2006.
- [7] K. Takakusaki, "Forebrain control of locomotor behaviors", *Brain Res. Rev.*, vol. 57, pp. 192-198, 2008.
- [8] K. Nakajima, F. Mori, C. Takasu, M. Mori, K. Matsuyama and S. Mori: "Biomechanical constraints in hindlimb joints during the quadrupedal versus bipedal locomotion of *M-fuscata*", *Progress in Brain Research*, vol. 143, pp.183-190, 2004.
- [9] N. Ogihara: "Synthetic Study of Quadrupedal/Bipedal Locomotion in the Japanese Monkey", 4th Int. Symp. on Adaptive Motion of Animals and Machines (AMAM '08), Cleveland, USA, June 2008.
- [10] H. Aonuma and K. Niwa: "Nitric Oxide Regulates the Levels of cGMP Accumulation in the Cricket Brain", *Acta Biologica Hungarica*, vol. 55, pp. 65-70, 2004.
- [11] T. Fujiki, K. Kawabata, H. Asama: "Adaptive Action Selection of Body Expansion Behavior in Multi-Robot System using Communication", *Journal of Advanced Computational Intelligence and Intelligent Informatics*, vol.11, no.2, pp. 142-148, 2007.
- [12] M. Ashikaga, M. Kikuchi, T. Hiraguchi, M. Sakura, H. Aonuma and J. Ota: "Foraging Task of Multiple Mobile Robots in a Dynamic Environments Using Adaptive Behaviors in Crickets", *Journal of Robotics and Mechatronics*, vol. 19, no. 4, pp. 466-473, 2007.
- [13] S. Emoto, N. Ando, H. Takahashi, R. Kanzaki: "Insect-Controlled Robot -Evaluation of Adaptation Ability-", *Journal of Robotics and Mechatronics*, vol. 19, no. 4, pp. 436-443, 2007.
- [14] M. Iribe, K. Osuka: "Design of the Passive Dynamic Walking Robot by Applying its Dynamic Properties", *Journal of Robotics and Mechatronics*, vol. 19, no. 4, pp. 402-408, 2007.
- [15] A. Ishiguro, M. Shimizu, T. Kawakatsu: "A Modular Robot That Exhibits Amoebic Locomotion", *Robotics and Autonomous Systems*, vol. 54, pp. 641-650, 2006.

# Steering Committee Report on the *Mobiligence* Program

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\*<sup>5</sup>Osaka University, \*<sup>6</sup>Asahikawa Medical College, \*<sup>7</sup>Hokkaido University

## 1. Missions

The missions of the steering committee are as follows:

- Establish goals for the *Mobiligence* Program
- Plan and coordinate research
- Evaluate research progress and consult
- Determine the procedures for the public invitation of proposed topics
- Organize symposia and research meetings for the purpose of developing related research
- Plan publicity of research results
- Encourage close collaboration among researchers, i.e., information exchange, mutual understanding, and communication
- Plan international research and lectures by members of academic societies and announce interim and ex post evaluations of progress
- Devise programs to encourage fused collaboration among biologists and engineering scientists and establish a research center and research organization

## 2. Summary of 2009 Activities of the Steering Committee

Research subjects were coordinated in each group to facilitate the fused collaboration between biologists and engineering scientists, which characterizes this program, and joint group meetings and open group meetings were organized to promote the inter-group collaboration effectively. Following events were organized; an international symposium, a domestic closed symposium for internal review, tutorials, workshops, and seminars. The internal review to the research activities of each project was performed. Many organized sessions are organized at international and domestic conferences. A series of text books (four volumes) on *Mobiligence* were planned, edited and publicized. The homepage for publicity and the database to record the activities in the program were maintained and updated. Research report was edited and published. Activities of Junior Academy of the *mobiligence* program were supported.

## 3. Steering Committee Meetings and WGs

The following Steering Committee meetings were held:

- 1<sup>st</sup> Steering Committee Meeting  
Nov. 21st, 2009, 14:00-15:00  
at Awaji Yumebutai International Conference Center
- 2<sup>nd</sup> Steering Committee Meeting  
Mar. 3rd, 2010, 12:30-13:30  
at Hotel Taikanso in Matsushima

## 4. Publication Committee Meeting

The following publication committee meeting was held for publication of the text book series on *Mobiligence*:

- 1st Publication Committee Meeting  
Nov. 20th, 2009, 12:20-13:30  
at Awaji Yumebutai International Conference Center

## 5. Publication of the Text Book on *Mobiligence*

A series of the text books (four volumes) on *Mobiligence* were publicized at the end of February, 2010 from Ohmsha Ltd.. (Fig. 1)

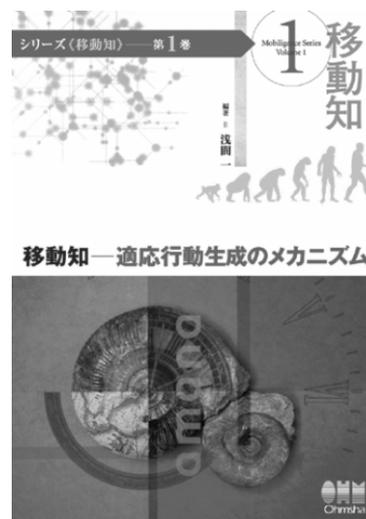


Fig. 1 Cover page of the *Mobiligence* text book

## 6. Organization of Symposia

### 6.1 International Symposium

The third International Symposium on *Mobiligence* was held at Awaji Yumebutai Conference Center, Japan on Nov. 19-21, 2009. Organized sessions organized by each group of the *Mobiligence* program were held, which include 3 invited speeches, 26 oral presentations, and 81 poster presentations and discussions. The invited speakers are; Joel W. Burdick (California Institute of Technology, USA), Martin S. Fischer (Friedrich-Schiller-Universität (Germany), and Yoshiharu Yamamoto (Univ. of Tokyo, Japan). Individual research outcome was presented in the oral and poster sessions by the members of *Mobiligence* program. A night session was organized by Junior Academy of the *Mobiligence* program. Total number of participants was 137. The presentations and discussions were recorded and publicized on the internet broadcasting system[1]. Figure 2 shows a presentation in the third International Symposium on *Mobiligence*.



Fig. 2 Presentation in the International Symposium

## 6.2 Domestic Closed Symposium

A symposium for internal evaluation was held in Hotel Taikanso in Matsushima, Japan, on Mar. 1-3, 2010. Oral and poster presentations on the research progress in 2009 of all the subjects in the *Mobiligence* program were made by each research leader and members. They were all reviewed by the review committee members and the steering committee members. Prof Minoru Asada (Osaka Univ., Japan) gave an invited talk. A night session was also organized by Junior Academy of the *Mobiligence* program. Total number of participants was 113.

## 7. Publicity

### 7.1 Organization of Special Issues of Journals

A special issue on Mobiligence was organized in the following journal and magazine:

- Advanced Robotics, International Journal, Vol.23, No.5 (2009), 5 papers
- Japanese Journal of the Society of Instrument and Control Engineers, Vol. 48, No. 9, (2009), 7 papers

The selected papers which were presented at the third International Symposium on Mobiligence will be published in the special issue of Journal of Robotics and Autonomous Systems.

### 7.2 Organization of Workshops in International Conferences

Workshops were planned and held in the following international conferences:

- Workshop on Future Trends of Mobiligence: Adaptive Motor Function through Dynamic Interactions among the Body, Brain and Environment, 2009 IEEE International Conference on Robotics and Automation (ICRA 2009), Kobe, Japan, May (2009), workshop, 6 papers
- Workshop on Mobiligence: Social Adaptive Functions in Animals and Multi-Agent Systems, 2009 IEEE/RSJ International Conference on Intelligent Robotics and Systems (IROS2008), St. Louis, USA, Sep. (2009), workshop, 9 papers

### 7.3 Session Organization in Domestic Conferences

Organized Sessions on Mobiligence were organized in the following domestic conferences:

- 2009 JSME Robotics and Mechatronics Division Annual Conference, Fukuoka, Japan, May 2009, 7 posters
- 2009 RSJ Annual Conference, Yokohama, Japan, Sep. 2009, 6 papers
- 19th Intelligent System Symposium, Aizu, Japan, Sep. 2009, 4 papers
- 2009 SICE Systems and Information Division Annual Conference, Yokohama, Japan, Nov. 2009, 4 papers
- 2009 SICE System Integration Division Annual Conference, Tokyo, Japan, Dec. 2009, 15 papers
- 2010 SICE Decentralized Autonomous Systems Symposium, Nagoya, Japan, Jan. 2010, 6 papers

## 7.4 Other Publicity Activities

The home page of the *Mobiligence* program was updated accordingly[2], database on research achievements[3] and activity records was maintained and presented on the web site.

The brochure of the *Mobiligence* program including subscribed research groups was published and distributed as well as call for proposals for the new subscribed research. The report, this volume, on the research activities of the *Mobiligence* program in 2009 was edited and published. The concept of the Mobiligence and current research outcome were broadcasted through the internet broadcasting system[1].

## 8. Organization of other Seminars, Tutorials and Workshops

To accelerate the fused collaboration and to foster young scientists and students who are doing *mobiligence* research, following seminars, tutorials, and workshops were arranged and held:

- Tutorial “Adaptation for Environment – Prediction and Internal Models”  
May 24th, 2009, 13:00-17:00 in 2009 JSME Robotics and Mechatronics Division Annual Conference at Fukuoka Convention Center
- Seminar of the Group “Common Principle”  
June 3rd, 2009, 10:30-17:00 at Toyonaka Campus of Osaka Univ.
- 44th Seminar of SICE Division of Autonomous and Decentralized Systems “Network and Interaction”  
June 19th, 2009, 13:30-16:00 at Hongo Campus of the Univ. of Tokyo
- 44th Seminar of SICE Division of Autonomous and Decentralized Systems “Network and Interaction”  
June 19th, 2009, 13:30-16:00 at Hongo Campus of the Univ. of Tokyo
- Seminar of the Group “Physical Adaptation”  
July 20th, 2009, 10:30-17:00 at Doshisha Univ.
- Seminar of the Group “Adaptation for Environment”  
Aug. 28th 14:00-30th 12:00, 2009 at Tokiwa Hotel
- Open Symposium “Hot Encounter of Animal Ethology with Robot Engineering”  
Nov. 27th, 2009, 16:30-19:00 in 28th Annual Meeting of the Japan Ethological Society at Tsukuba Univ.

- Tohoku University RIEC workshop on “Understanding of Order Generation of Adaptive behaviors in Biological System by the Constructive Approach”  
Dec. 18th 13:30 – 19th 12:30, 2009, at RIEC, Tohoku University, Sendai, Japan
- Seminar of the Group “Social Adaptation”  
Feb. 1st 10:20-16:00, 2010, at RIES, Hokkaido Univ.

## 9. Review

The research progress, outcome, and the collaboration between biology and engineering were reviewed by the following international and domestic reviewers in the third international symposium, and by the domestic reviewers in the domestic closed symposium:

- Domestic reviewers:  
Prof. Shinzo Kitamura (Hyogo Prefectural Institute of Technology), Prof. Shigemi Mori (National Institute for Physiological Sciences), and Prof. Ryoji Suzuki (Kanazawa Institute of Technology)
- International reviewers:  
Prof. Sten Grillner (Karolinska Inst.), Prof. Avis H. Cohen (Univ. of Maryland), Prof. Rolf Pfeifer (Univ. of Zurich)

## 10. Activity Support for Junior Academy of the *Mobiligence* program

The steering committee supported the following activities of the Junior Academy of the *mobiligence* program:

- Organized Session in the 2010 SICE Decentralized Autonomous Systems Symposium, Nagoya, Japan, Jan. 2010, 3 papers
- Creating Glossaries (embodied in the text book on Mobiligence)

## 11. Planning of Future Program for Mobiligence

Planning and discussion on new projects was made by a working group which consists of a part of the steering committee, to expand the research area of Mobiligence after the term of the Mobiligence program terminates

## References

- [1][http://www.netrush.jp/science\\_top.htm](http://www.netrush.jp/science_top.htm)  
 [2][http://www.robot.t.u-tokyo.ac.jp/mobiligence/index\\_e.html](http://www.robot.t.u-tokyo.ac.jp/mobiligence/index_e.html)  
 [3]<http://www.robot.t.u-tokyo.ac.jp/mobiligence/act/index.html>



# Group A: Adaptation to Environment

## Annual Report

Koji ITO

Tokyo Institute of Technology, Japan

### I. RESEARCH PROJECT

The aim of Group A is 1) to clarify the brain-nervous mechanisms for creating appropriate hypothesis to constrain behaviors based on the accumulated experiences under unpredictable environments, 2) to analyze the motor control mechanisms producing adaptive behaviors corresponding to dynamical environments, and 3) to construct mathematical models of the adaptive sensorimotor coordination mechanism composed of the brain, body and environment. To perform the above aim, the group hangs the following research subjects.

Research subject A01: Modeling of intra-cerebral mechanisms for motor adaptation to unknown environments.

In order to generate adaptive behaviors in various environments, it is necessary to integrate the redundant degrees of freedom in the brain, body and environment based on changing contexts of situation. The research subject aims to elucidate the brain mechanisms of the sensorimotor coordination corresponding to the dynamic environments by the experimental, constructive and systematic approaches.

Research subject A02: Anticipatory adaptation of sensorimotor coordination.

To understand the sensorimotor coordination mechanism for environment cognition and appropriate motor adaptation, behavioral contexts and intrinsic factors (e.g., anticipation, intention, attention, affection, etc.) of subjects should be considered. The research subject aims to clarify the relationship between these intrinsic factors and sensorimotor adaptation under unfamiliar environments.

### II. RESEARCH GROUPS

Group A consists of two planned and seven subscribed research groups. The research groups are reformed in this year based on the middle evaluation.

#### - Planned Research Groups

- 1) A01-01 Koji Ito (Tokyo Institute of Technology)  
Modeling of intra-cerebral mechanisms for motor adaptation to unknown environments
- 2) A01-02 Toshiyuki Kondo (Tokyo University of Agriculture and Technology)  
Anticipatory adaptation of sensorimotor coordination

#### - Subscribed Research Groups

- A01-11 Toshiya Matsushima (Hokkaido University)  
Optimal motor investments: algorithm of instantaneous gain rate computation
- 3) A01-12 Yasuharu Koike (Tokyo Institute of Technology)  
Learning and control model in consideration of inconsistency between vision and tactile
- 4) A01-13 Tadashi Ogawa (Kyoto University)  
The role of the prefrontal cortex in advancing cognitive adaptation under unknown circumstances
- 5) A01-14 Yasuji Sawada (Tohoku Institute of Technology)  
Study of optimization for the cooperative adaptation between motions of two persons by mutual tracking experiments
- 6) A01-15 Akira Murata (Kinki University, School of Medicine)  
Brain mechanisms for recognition of bodily self and others
- 7) A01-16 Tetsunari Inamura (National Institute of Informatics)  
Multimodal sensorimotor integration and behavior induction between other and self based on mirror neuron model
- 8) A01-17 Jun Tani (Brain Science Institute, RIKEN)  
Understanding "Organic Compositionality" in cognitive brain mechanisms

### III. RESEARCH RESULTS

#### (1) Learning by motivated observation

"Learning by observing" is an important feature confirmed in human motor learning. Matter et al. reported that observing someone else's behavior affects even subconsciously on the consecutive motor learning. In their experiment, the subjects who observed a video beforehand, in which someone engaged in an arm reaching task under a viscous curl force field demonstrated rapid adaptation compared with the subjects without the observation. Their experiment, however, had not constrained whether the subjects had intention to imitate the observed behavior.

We experimentally examined the effects of observing expert's movement beforehand, and of providing an instruction to have motor imagery during the observation. As well as Matter's work, arm reaching movement under viscous curl force field was used as the learning task. Twelve subjects participated in the experiment. They were randomly-assigned into three groups; (1) Rest, (2) Observation, and (3) Motivation, respectively. The Observation and Motivation group asked to look at a video, in which an expert engaged in the reaching movement under the force field. In addition, the Motivation group subjects were provided with an instruction that they have to tackle the same task just after the observation.

The experimental result shows that the subjects who experienced a preceding observation (i.e. Observation or Motivation group) outperformed the subjects without the observation, especially in the latter stage of the motor learning (i.e. final performance level). Moreover, the Motivation group subjects demonstrated a rapid performance improvement than the others in the early stage of the motor learning.

(2) Electroencephalogram (EEG) - functional electrical stimulation (FES) system for stroke motor rehabilitation

Stroke is a leading cause of adult disability which induces functional deficits in motor control. Motor learning is considered as the basic principle for rehabilitation, but there are few systems which focus on motor learning for severely paralyzed patients. We proposed a BCI rehabilitation system which used electroencephalogram (EEG) of motor intention (event related desynchronization: ERD) to control functional electrical stimulation (FES) of sensory feedbacks. The proposed system (EEG - FES system) could accelerate motor recovery by dynamically variable FES amplitude. We had performed fundamental researches about ERD. Here, we will report the short term (one day) training effect for a severely impaired patient.

One stroke patient (male; age = 55 years; hemiplegia duration = 30 months) was recruited. The patient had infarction in brain stem and had paralysis in his left side. Tibialis anterior muscle was aimed in the training and this subject had severely impaired in this muscle (SIAS, foot-pat score; 0/5). In the EEG - FES training, the subject performed twenty trials (one trial = 1 minute) with repeating attempt of dorsal extension. During the trial, the subject repeated dorsal extensions and rose the bar display and FES amplitude as much as possible (Updated every 500 msec).

Before and after training, the subject performed repetition of dorsal extensions with cue presence (without bar display and FES). One trial (10 sec) contained cue absence (5 sec, no motion) and cue presence (5 sec, motion). In total, thirty trials data were recorded in succession.

Comparing before and after training, the quality of motion was significantly improved. Before training, the knee joint was moved and the ankle joint not activated. In contrast, after training, the clear ankle joint movement was observed. Before training, there was little myoelectric activity during the motion (5 - 10 sec), but the activity after training was much improved.

These results support the use of EEG - FES system for severely paralyzed muscles. The EEG - FES system had changed the quality of ankle motion. The mechanism of the improvement is not clarified, but it may be due to brain plasticity by dynamically controlling functional electrical stimulation (FES) amplitude accordance with motor intention. It is crucial to note that this study is only from one stroke subject with short term training. More studies with different lesion locations and chronicities are needed to evaluate the effect of EEG - FES system.

#### IV. MEETING AND OTHERS

##### - Joint Meeting of Group A and B

Date: Dec. 18, 13:30 - Dec. 19 12:30, 2009.

Place: Meeting room, Research Institute of Electrical Communication, Tohoku University.

Attendee: 30 members of group A and B.

Presenters:

- 1) Prof. Kusaki Takakusaki, Asahikawa Medical College.
  - 2) Dai Yanagihara, University of Tokyo
  - 3) Tetsuro Funato, Doshisha University
  - 4) Masahiro Shimizu, Tohoku University
  - 5) Jun Ota, University of Tokyo
  - 6) Toshiya Matsushima, Hokkaido University
  - 7) Yasuharu Koike, Tokyo Institute of Technology
  - 8) Koji Ito, Tokyo Institute of Technology
  - 9) Masafumi Yano, Tohoku University
- Free discussion.

##### - Half Day Tutorial in ROBOMECH 2009 at FUKUOKA

Date: May. 24, 13:00 - 17:00, 2009.

Place: Fukuoka International Congress Center,  
Attendee: 80.

Presenters:

- 1) Toshiyuki Kondo (Tokyo University of Agriculture and Technology)
- 2) Yasuharu Koike (Tokyo Institute of Technology)
- 3) Tetsunari Inamura (National Institute of Informatics)
- 4) Koji Ito (Tokyo Institute of Technology)

# Modeling of Intra-cerebral Mechanisms for Motor Adaptation to Unknown Environment

Koji Ito and Manabu Gouko (Tokyo Institute of Technology)

## I. INTRODUCTION

Even if we situated in unfamiliar environments with any kinematic and/or dynamic transformations, we can adapt to them in several trials-and-errors. As a consequence of the motor learning process, we can acquire a neural representation of the relation between motor command and the movement, i.e. internal model of the environment. However, it is still open question to explain the neural representation, i.e. how the internal models are represented in our brains.

For instance, we can instantly manipulate any objects by using any tools even though there are a number of combinational possibilities. In addition, we can select an appropriate internal model according to the contextual information of the environments. It implies that there is an intrinsic prediction and motor adaptation mechanisms in the motor area of our brain.

The A01-01 group aims to clarify the intra-cerebral mechanisms to recognize unfamiliar environments and to generate suitable motor commands, through psychophysical experiments and computational modeling of human movement learning. Additionally, a rehabilitation system for the stroke patient based on the motor adaptation mechanisms is also developed. In this report we explain about our recent research topics.

## II. Cooperative mechanisms of internal model control and impedance control under force fields

When performing the arm movements under the dynamical environments (ex. object manipulation and tool-use), CNS needs to combine internal model control and impedance control in a feedforward manner. Recently, in the area of human motor control and computational neuroscience, many experiments which investigate motor adaptation of human arm movements under the dynamical environments have been performed. However, the mechanism which CNS combines two control strategies (internal model control and impedance control) has not been clarified. In our research, we setup the mixed force field by composing the velocity-dependent force field and position-dependent force field. Then we analyzed motor adaptation of arm movements under the force field [1]. In addition, we also performed the numerical experiment by using the computational model of human arm movements to support the psychophysical experimental results [2].

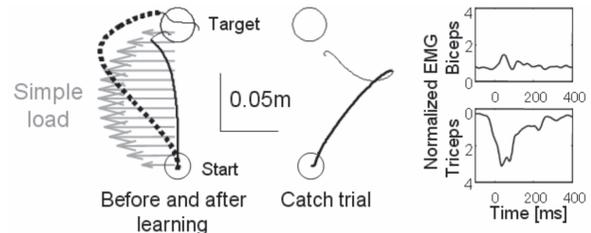


Fig. 1. Reaching movements under the simple environment.

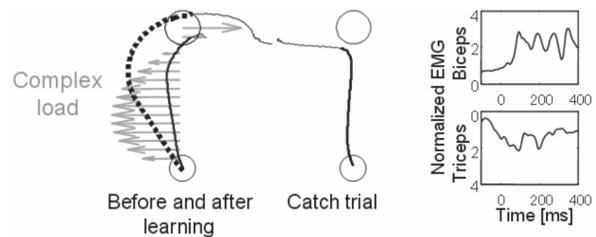


Fig. 2. Reaching movements under the complex environment.

### A. Psychophysical experiment on reaching movements under force fields

Several students participated in the experiment. In the experiment, the subjects performed point-to-point reaching movements in the horizontal plane. The subjects moved their right hand from the start point to the target point quickly. The movement distance was 0.125m. The movement time was  $300 \pm 50$ ms. As a experimental apparatus, we used the robotic manipulandum [1]

In the experiment, the subjects learned reaching movements under two types of force fields. One is the velocity-dependent force field (the ' simple environment ') which generates the load depending on the hand velocity of the subject. The other is the mixed force field (the ' complex environment ') which generates the load depending on both the hand velocity and position. The load pattern of the mixed force filed is more complex than that of the velocity-dependent force fields because the load direction is reversed from left to right during the movement as shown in fig.2.

Fig.1 and fig.2 show the experimental results. In each figure, the left figure shows the hand trajectories before and after learning (dotted line: before, solid line: after) and the hand trajectory in the catch trial. The right figure shows EMG data after learning. In the mixed force field (fig.2), the hand trajectory in the catch trial was not curved compared with the result in the velocity-dependent force filed and the agonist

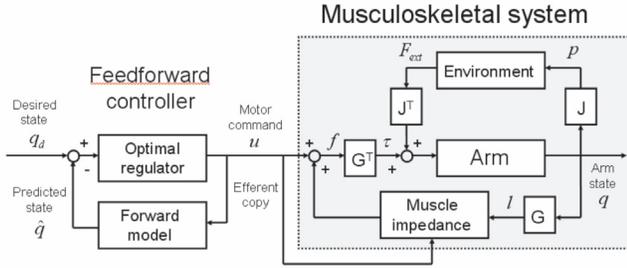


Fig. 3. Simulation model.

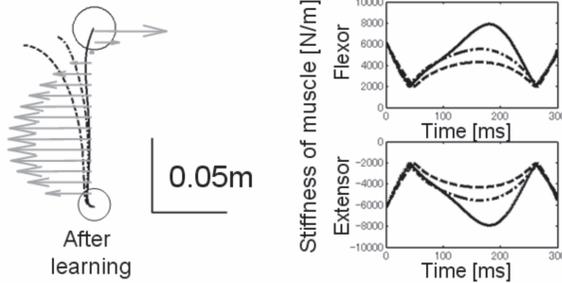


Fig. 4. Simulation results under the complex environment.

and antagonist muscles were co-contracted. This indicates the subject did not learn the internal model of the mixed force field accurately and the subject compensated the load by using impedance control. Thus, this result suggests that the valance how CNS combines two control strategies are changed depending on the complexity of the force field.

### B. Numerical experiment by using computational model of human arm movements

Next, we performed the numerical experiment by using computational model of human arm movements to understand the mechanism how CNS combines internal model control and impedance control. Fig.3 shows the structure of our model. The controller is composed of the optimal regulator and the forward model. The motor command is calculated by the internal simulation by the forward model. The optimal regulator calculates the optimal feedback gain which minimizes the cost function, which is composed of the ‘ end-point error ’ term and the ‘ energy ’ term. The arm is given three types of inputs which are the motor command by CNS, the load from the environment and the feedback force by the muscle impedance [2].

Fig.4 shows the simulation results of reaching movements under the mixed force field. The left figure shows the hand trajectories after learning and the right figure shows the muscle impedance of shoulder. In the simulation, we setup three levels of the weight of the cost function. In Fig.4, the solid lines represent the results when the wight of ‘ end-point error ’ is much bigger than the others. In this case, clearly, the muscle impedance becomes higher and the muscles are co-contracted.

Thus, from the view point of optimal control, it is specu-

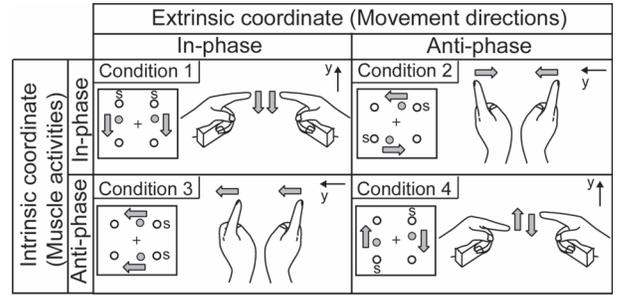


Fig. 5. Task conditions based on the homologous muscle activities and the movement directions.

lated that humans give more wight to ‘ end-point error ’ than ‘ energy ’ in the complex environment, and as a results, the arm impedance becomes higher compared with the result in the simple environment.

### III. Bilateral interaction for coordinated movement

In daily life, human performs many kinds of bilateral coordinated movements. Typing and swing a bat are good examples of bilateral movements which are combined spatially and temporally. When central nervous system (CNS) generates bilateral movements, connections and interactions between right and left control systems (ex. right and left hemispheres) are important to integrate the bilateral information and construct the bilateral coordination. However, when we try to control the bilateral body parts with independent movement patterns, the movements of one side can be affected by the contralateral movements through the connections and interactions. That is, in order to control the bilateral coordinated movements appropriately depending on the movement pattern, CNS need to modulate the interhemispheric interaction and change the coordination of bilateral bodies. In this study, we investigated the relationship between bilateral movement pattern and interhemispheric interaction.

In our experiments, subjects performed cyclic extension-flexion movements at 0.5Hz with bilateral index fingers. We estimated amplitude changes of left finger as the strength of the interhemispheric interaction while the subjects modified the amplitude of right finger voluntarily. There were 4 conditions based on the relative timing of homologous muscles and the relative directions of right and left finger tips (fig.5).

Fig.6 shows the results of the right and left finger ‘ s amplitude changes. The amplitude modifications of right finger were equivalent among the all conditions but the response of left finger in condition 4 was significantly weaker than those of the other conditions. These results suggested that CSN has a mechanism to modulate the interhemispheric interactions depending on the bilateral movement patterns. If the bilateral movement is represented as the in-phase movement by homologous muscle activities (intrinsic coordinate information) or the movement directions (extrinsic coordinate information), the common information would be interacted between bilateral control systems to generate the coordinated coupling. On the other hand, like the condition 4, when

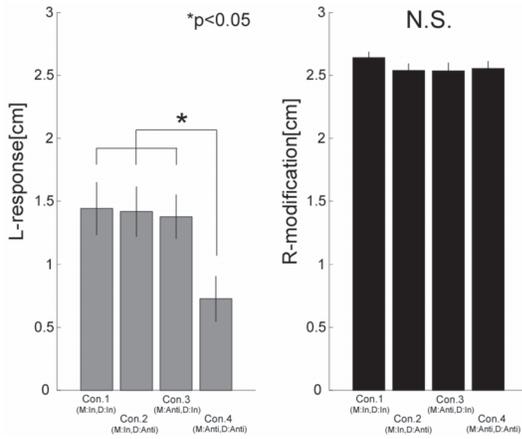


Fig. 6. Amplitude modifications of right finger (right fig.) and left finger response (left fig.) in each condition.

there was no common information, CNS would suppress the interhemispheric interaction to generate the independent bilateral movements easily. These modulation manners for interhemispheric interaction indicate the functional aspect in CNS during the bilateral coordinated movement control.

In addition, we also evaluated the bilateral movement stability by estimating variability between right and left movement profiles. The variability during intrinsic in-phase movements (i.e. condition 1 and 2) was smaller than that during intrinsic anti-phase movements (i.e. condition 3 and 4). In other words, homologous muscle movements were more stable than non-homologous muscle movements. That is, there might be some kind of qualitative differences among condition 1, 2 and 3 in which the strength of the left finger's responses were equivalent.

In order to investigate the difference, we focused on the interaction information in each condition. The following results were obtained: only error information in visual coordinate could interact between bilateral control systems in condition 3. On the other hand, in condition 1 and 2, not only the error information but also movement amplitude information in muscle coordinate could affect the contralateral control system. These results suggested that bilateral coordination was constructed by multiple interhemispheric interactions and what information was shared between bilateral control systems would strongly influence the coordination of the bilateral movements.

In the future, we need to investigate more concrete brain site which relates to the interhemispheric interaction during coordinated movements by using fMRI imaging.

#### IV. Electroencephalogram (EEG) - functional electrical stimulation (FES) system for stroke motor rehabilitation

Stroke is a leading cause of adult disability which induces functional deficits in motor control. Motor learning is considered as the basic principle for rehabilitation, but there are few systems which focus on motor learning for severely paralyzed patients. We propose a BCI rehabilitation system which uses electroencephalogram (EEG) of motor intention (event related desynchronization: ERD) to control functional

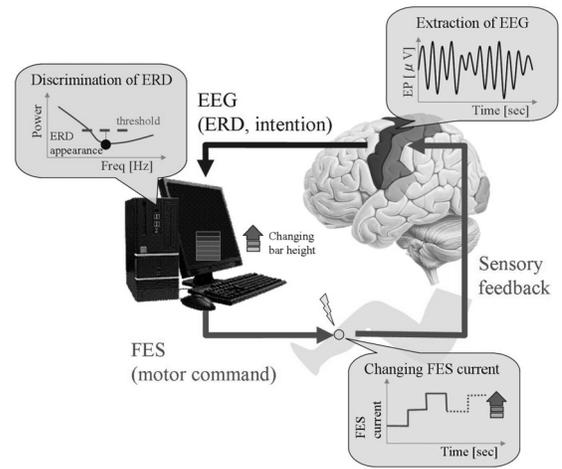


Fig. 7. Conceptual explanation of EEG-FES system.

electrical stimulation (FES) of sensory feedbacks (fig.7). The proposed system (EEG - FES system) will accelerate motor recovery by dynamically variable FES amplitude. We performed fundamental researches about ERD [3], [4]. In this paper, we will report the short term (one day) training effect for a severely impaired patient.

##### A. Method

One stroke patient (male; age = 55 years; plegia duration = 30 months) were recruited. The patient had infarction in brain stem and had paralysis in his left sides. Tibialis anterior muscle was aimed in the training and this subject had severely impaired in this muscle (SIAS, foot-pat score; 0/5). In the EEG - FES training, the subject performed twenty trials (one trial = 1 minute) with repeating attempt of dorsal extension. During the trial, the subject repeated dorsal extensions and rose the bar display and FES amplitude as much as possible (Updated every 500 msec).

Before and after training, the subject performed repetition of dorsal extensions with cue presence (without bar display and FES). One trial (10 sec) contained red cue absence (5 sec, no motion) and red cue presence (5 sec, motion). In total, thirty trials data were recorded in succession.

##### B. Result and discussion

Fig.8(a) and (b) are the 10 samples of before and after the training of 2-D leg data. Comparing these two figures, the quality of motion seemed to be significantly changed. In fig.8 (a), the knee joint seems to be moved and the ankle joint seems not to be activated. In contrast, fig.8 (b) shows the clear ankle joint movement. fig.8 (c) and (d) illustrates the one of low myoelectric activity over left tibialis anterior muscles (fig.8 (c): before training, (d): after training). In fig.8 (c), there was little muscle activity during the motion (5-10 sec), but the activity had improved after the training.

These results support the use of EEG - FES system for severely paralyzed muscles. The EEG - FES system had changed the quality of ankle motion. The mechanism of the improvement is not known, but it may be due to

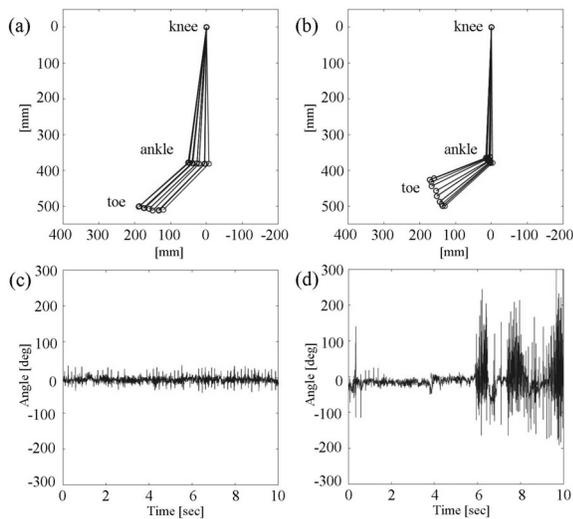


Fig. 8. Comparison of motion analysis and EMG: (a) leg motion of before training, (b) leg motion of after training, (c) raw EMG activity of before training, (d) raw EMG activity of after training.

brain plasticity by dynamically controlling functional electrical stimulation (FES) amplitude accordance with motor intention. It is crucial to note that this study is only from one stroke subject with short term training. More studies with different lesion locations and chronicities are needed to evaluate the effect of EEG - FES system.

## V. Environmental modeling and identification for autonomous mobile robot

In research on autonomous mobile robots, many studies on localization and navigation tasks have been conducted. These tasks are generally performed using prior knowledge (e.g., a map of the environment) based on visual and position data of its environment. For example, a robot that works in several environments, such as different rooms, needs knowledge about each environment. If the robot can recognize that it is in a known environment, it can use the map of the surroundings. On the other hand, if the robot recognizes that it is in an unknown environment, it will try to build a new map of the environment. Thus, it is important for a robot to identify which environment it is currently in so that it can work efficiently. Autonomous mobile robots should be able to identify their environments by themselves.

An easy method of identifying multiple environments is to set landmarks in each environment. The robot can identify which environment it is in by comparing the landmarks; however, this requires space and time for installation. Another method is to use environmental modeling and comparison (fig.9). The robot makes a model of its current environment and compares it against many stored environmental models. For highly accurate recognition, this method requires a model that can represent the characteristics of a real environment. Moreover, the model must be easier to make than a new map.

The characteristics (e.g., size and layout) of each environment appear as the form of the environment if the environment is a closed region surrounded by walls. On the

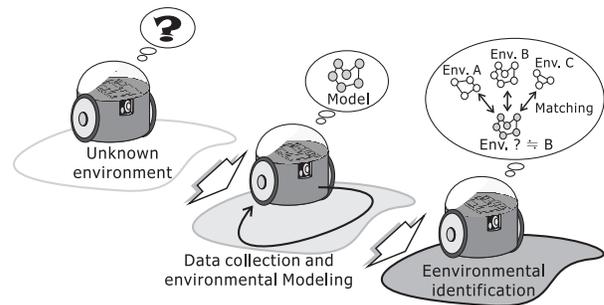


Fig. 9. Overview of the environmental identification.

assumption that the environment is a closed region, several studies on environmental modeling and identification have been done [5].

In this study, we identify an environment by using a model based on changes in sensory information [6]. The model is built from changes in sensory data observed by the mobile robot during wall-following movements. Our method is targeted at mobile robots that have only low-sensitivity short-range sensors because there are cost advantages if such a simple robot can identify its environment.

In experiments, we confirmed the effectiveness of our method by applying it to a mobile robot having only low-sensitivity infrared sensors. We compared the performance of our method with AEM, which is one of the environmental identification methods proposed by Yamada and Murota[5]. The maximum rate for our method was 99% for 13 environments. The recognition rate of AEM was 77.9%. The result showed that our method had higher performance[6].

In our method, the size of the robot and the arrangement of the sensors and the sensing area affect the model. We will investigate these effects in the future.

## VI. CONCLUSION

In the paper, we shortly reported our recent research results. We continue to clarify the intra-cerebral mechanisms for recognizing unfamiliar environments and/or generating suitable motor commands, through psychophysical motor learning experiments and computational modeling of human movement.

## REFERENCES

- [1] N. Tomi, M. Gouko, T. Kondo and K. Ito, "Inaccuracy of internal models in force fields and complementary use of impedance control," SICE, vol.44, no.11, pp.896-904, 2008 (in Japanese).
- [2] N. Tomi, M. Gouko and K. Ito, "Regulation mechanisms of arm impedance by using optimal control under force fields," Technical Report of IEICE, NC2008-139, pp.213-218, 2009 (in Japanese).
- [3] M. Takahashi, M. Gouko and K. Ito, "Fundamental research about electroencephalogram (EEG) - functional electrical stimulation (FES) rehabilitation system," Proc. of ICORR2009, 2009.
- [4] M. Takahashi, M. Gouko and K. Ito, "Electroencephalogram (EEG) and functional electrical stimulation (FES) system for rehabilitation of stroke patients," Proc. of CBMS2008, pp.53-58, 2008.
- [5] S. Yamada, and M. Murota, "Unsupervised learning to recognize environments from behavior sequences in a mobile robot," Proc. of ICRA98, pp.1871-1876, 1998.
- [6] M. Gouko and K. Ito, "Environmental modeling and identification based on changes in sensory information," Proc. of ICAIS 2009, pp.79-85, 2009.

# Anticipatory adaptation of sensorimotor coordination

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## I. INTRODUCTION

*Learning* is an essential feature of living creatures, especially humans. Even though we are situated in unfamiliar environments which have kinematic or dynamic sensorimotor transformations, we can adapt to them through several trial and error. As a consequence of the active motor learning process, our brain would have neural representations of the relationship between our motor commands and body movements, i.e., *internal models* of various environments. To make clear how the internal model is structured and represented in our brains, human motor learning under visually or physically perturbed environments has been widely and intensively studied in psychophysics and neuroscience research fields. In these basic science research, some of interesting characteristics concerning human motor learning have been reported. One of the topic we are interested in is the effect of training order on motor learning. It implies that varying training schedules unpredictably may have a positive effect on simultaneous learning of conflicting sensorimotor adaptation tasks. Another topic to which we paid attention is the effect of observing expert movement before motor learning. This report describes about the two research topics (i.e. simultaneous learning of conflicting visuomotor rotations, and motor learning by observing) that our group did in the two years.

## II. SIMULTANEOUS LEARNING OF CONFLICTING VISUOMOTOR ROTATIONS

We focused particularly on the effect of successive experiences on simultaneous learning of conflicting visuomotor rotations. It has been reported that simultaneous learning of two conflicting visuomotor transformation tasks presented in random order was significantly better than the training with alternating order, even if the total number of experiences was the same in each case [3]. However, it remains unclear why the random training schedule aids simultaneous learning of conflicting tasks. In this study, we assumed that the alternating training schedule gave no opportunity to experience the same rotational transformation successively. To test this assumption, we compared three training conditions; the encountered rotational transformation type was (1) alternating with every trial (ALT1), (2) alternating with every two trials (ALT2), and (3) changed at random (RAND).

### A. Methods

Twelve subjects (eight males and four females,  $21.0 \pm 2.0$  years old, mean  $\pm$  SD) participated in the experiment with informed consent, but they know nothing about the purpose of the experiment. All subjects were right-handed and relatively experienced with the operation of a computer mouse.

In the experiment, the subjects were seated on a height-adjustable high-back chair. An LCD screen (Hewlett-Packard, hp2035) was placed on a flat table in front of the subjects. A computer mouse with a pen tablet apparatus (WACOM, PTZ-631W) was located at the right-hand side on the table.

During the learning task, a cursor and a target were displayed on the screen. The cursor was a small solid white circle (diameter approximately 4.0mm) on a black background. In each trial, subjects could see the cursor at all times, but their hand movements were hidden by a partition. The target was displayed on the screen as a small solid green square (approximately 6.5mm on a side). At each trial, the target appeared at a position randomly selected from eight peripheral candidates at 45-degree intervals.

In the experiment, subjects were asked to move the computer mouse device to move the cursor to the target as quickly as possible. However the cursor position  $(X_c, Y_c)$  was determined by the displacement of the computer mouse  $(x, y)$  with the following rotational transformation:

$$\begin{pmatrix} X_c \\ Y_c \end{pmatrix} = \kappa \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \quad (1)$$

where  $\kappa$  corresponds to an amplification of the hand displacement. Before starting the experiment, each subject was asked to adjust the parameter regarding cursor movement to be as usual. Also,  $\theta$  is a rotation angle of -90, 0, or 90 degrees, here a clockwise rotation is assumed to be positive.

The learning task proceeded as follows.

- 1) The subject was asked to place the mouse device at the initial position indicated on the tablet.
- 2) At that time, the background of the screen was filled with blue (RGB #000080) or red (RGB #800000) in accordance with the rotational transformation presented in the next trial (i.e., CW90 or CCW90, respectively).
- 3) The subject clicked the mouse button. At the same time, one of the eight targets chosen randomly was displayed on the screen. Immediately, the subject started to move the mouse to direct the cursor toward the target.
- 4) When the cursor reached the target, the trial was terminated with the message, "Please return the mouse device to the home position."
- 5) The process was repeated until a series of trials was completed.

In the experiment, one *set* consisted of 32 trials ( $N_S = 32$ ). Thus, the eight targets were randomly chosen four times

each in a set; however, the same target was not presented consecutively.

In the experiments, all subjects were instructed to move the cursor quickly on a straight trajectory to the target. To assess each subject’s performance, the time required to reach the target (reaching time;  $T_i$  [sec]) and accumulated directional error ( $E_i$  [rad]) measured in a trial were used (subscript  $i$  denotes the trial number). The accumulated directional error  $E_i$  was defined as

$$E_i = \sum_{l=1}^{L_i} |\phi(l) - \psi|,$$

$$\psi = \arctan \left[ \frac{Y_g - Y_c(0)}{X_g - X_c(0)} \right],$$

$$\phi(l) = \arctan \left[ \frac{Y_c(l) - Y_c(0)}{X_c(l) - X_c(0)} \right],$$

where  $X_g$  and  $Y_g$  represent the target coordinates, and  $X_c(l)$  and  $Y_c(l)$  denote the cursor coordinates sampled at discrete time step  $n$ . Thus,  $X_c(0)$  and  $Y_c(0)$  correspond to the initial cursor position.  $L_i$  is the total number of time steps in the  $i$ -th trial.

Before starting the simultaneous training experiment, all subjects were asked to accustom themselves to the task without visuomotor rotation (i.e., in the NULL condition). After the familiarization, subjects executed one set in the NULL condition to determine baseline performance of each subject.

Subsequently, we started the simultaneous training experiment. During the training, the subjects were exposed to one of two conflicting visuomotor rotations, CW90 or CCW90, depending on their training schedules. As specified in Table I, the subjects were randomly assigned to three groups; (1) Group ALT1 with a visuomotor rotation alternating every trial ( $n = 4$ ), (2) Group ALT2 with a visuomotor rotation alternating every two trials ( $n = 4$ ), and (3) Group RAND with a visuomotor rotation randomly selected at every trial ( $n = 4$ ). The training iteration consisted of two sessions of 10 sets each, with a 90-minute rest interval between the sessions.

TABLE I  
TRAINING PROCEDURE OF THE EXPERIMENT.

	ALT1 ( $N = 4$ )	ALT2 ( $N = 4$ )	RAND ( $N = 4$ )
first half (1st-10th)	alternating (trial by trial)	alternating (every two trials)	random
rest	90 min.		
second half (11th-20th)	alternating (trial by trial)	alternating (every two trials)	random

## B. Results

To clarify whether the subjects could learn the two conflicting visuomotor rotations simultaneously, we analyzed the decrement in the averaged error rates between the first and last five training sets separately in the case of CW90 or CCW90. The error rates were also averaged across the subjects in each group. According to the results of ANOVA, we confirmed that the error rates were decreased significantly in all cases (training groups  $\times$  rotation types), ALT1 group (CW90:  $F_{1,38} = 5.95, p = 0.0195$ ; CCW90:  $F_{1,38} = 6.01, p = 0.0190$ ), ALT2 group (CW90:  $F_{1,38} = 36.2, p < 0.001$ ; CCW90:  $F_{1,38} = 13.8, p < 0.001$ ), and RAND group (CW90:  $F_{1,38} = 23.3, p < 0.001$ ; CCW90: ( $F_{1,38} = 22.7, p < 0.001$ ).

From another perspective, we analyzed the error rates among the training groups by ANOVA separately for each stage (i.e., the first or last five sets) and rotation type (CW90 or CCW90). Fig. 1 shows the comparison.

No significant differences appeared in the early stage (i.e., the first five sets) of CW90 ( $F_{2,57} = 2.58, p = 0.0844$ ) and CCW90 ( $F_{2,57} = 2.68, p = 0.0770$ ). Note that the level of significance was  $p = 0.05$ . In contrast, significant differences were confirmed in the later stage (i.e., the last five sets) of both rotation types; CW90 ( $F_{2,57} = 7.73, p = 0.00107$ ) and CCW90 ( $F_{2,57} = 6.31, p = 0.00334$ ). Accordingly, we executed multiple comparisons (*Bonferroni-Dunn* tests) with regard to the cases. The results of the multiple comparison were as follows: CW90 (ALT1 vs. ALT2:  $p = 0.0948$ , ALT1 vs. RAND:  $p = 0.00161$ , ALT2 vs. RAND:  $p = 0.00554$ ), CCW90 (ALT1 vs. ALT2:  $p = 0.212$ , ALT1 vs. RAND:  $p = 0.00506$ , ALT2 vs. RAND:  $p = 0.000733$ ). The significance level used here was  $p = 0.0167 (= 0.05/3)$ .

From these results, we confirmed a significant difference between the ALT1 or ALT2 and RAND groups, even though there were no significant differences in the early stage.

## III. LEARNING BY MOTIVATED OBSERVATION

Another important finding in human motor learning is *learning by observing*. As has been known as “seeing is believing” most of motor skills are highly dependent on visual information. We empirically know that observing experts’ movements gives rise to a fruitful effect on an improvement of the motor skill.

Matter *et al.* reported that observing someone else’s behavior affects even subconsciously on the consecutive motor learning [4]. In their experiment arm reaching movement under a viscous curl force field was adopted as the motor learning task. The subjects who observed the video beforehand, in which someone engaged in a reaching task under a clockwise force field demonstrated rapid adaptation compared with the subjects without the observation. Their experiment, however, had not constrained whether the subjects had intention to imitate the observed behavior.

In the meantime, recent neurophysiology has revealed that an identical brain region, i.e. *mirror neuron system*, would be activated in both case of observation and preparation of action [5], [6]. Calvo-Merino *et al.* reported that the brain

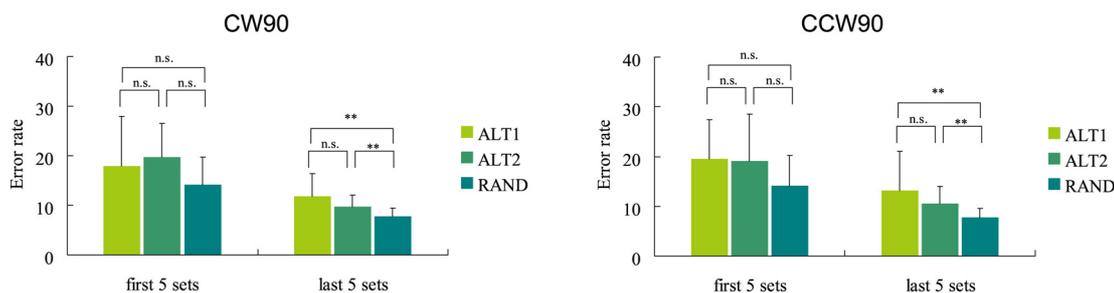


Fig. 1. Change in the average error rates between the first and last five sets under the three training conditions. (Left: averaged across CW90 trials. Right: averaged across CCW90 trials)

region was especially activated while observing/initiating well-mastered body movement (e.g. a professional dancer looks at someone else's dance performance) [7]. Vogt *et al.* reported that strong activation of the mirror neuron system was observed from beginners' brain, who engaged in imitative learning [8]. These findings seem to be inconsistent, but it implies that the effect of having motor imagery should be separately evaluated with the observation.

Based on these background, in the paper, we experimentally examined the effects of observing expert's movement beforehand, and of providing an instruction to have motor imagery during the observation.

#### A. Method

As well as Matter's work [4], arm reaching movement under viscous curl force field was used as the learning task in our experiment. Thus the hand in the force field will receive a viscous friction force in the direction rotated clockwise 90 degrees with respect to the hand velocity vector.

A subject holds and manipulates a force feedback device (Phantom Omni, SensAble Inc.) within the coronal plane which is parallel to a frontal screen. Using a LCD beam projector, a cursor, a target and a home position can be displayed on the screen.

In each trial, the subject firstly moves the cursor to the home position. After a second, a target emerges at one of three candidate positions with a uniform probability. The distance to each target from the home position is equivalent. As soon as the target appears the subject starts reaching movement using the haptic device. After the reaching or three seconds passed, the target disappears and the trial is over. Based on the cursor trajectory, accumulated trajectory error (i.e. the perpendicular distance from the ideal straight line) was calculated.

Twelve healthy male subjects (aged early 20s) participated in the experiment with their agreement. All subjects were right-handed and naive about the objective of the experiment.

As shown in Fig.2, before starting the experiment, all subjects experienced 36 trials without the force field to be accustomed to the reaching task. After the familiarization, they were randomly-assigned into three groups; (1) Rest, (2) Observation, and (3) Motivation, respectively.

The subjects in Observation and Motivation group asked to look at a video (four minutes), in which an expert engaged in

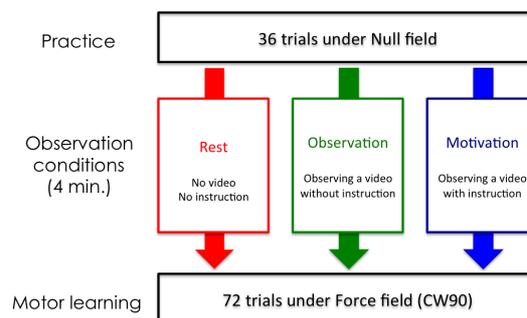


Fig. 2. Experimental procedure and conditions.

the reaching movement under the clockwise force field (i.e. identical to the learning task). The Rest group subjects took four minutes rest, instead.

In addition, the subjects in Motivation group were provided with an instruction that they have to tackle the same task just after the observation. Needless to say, they were not informed about the perturbation.

#### B. Results

Experimental results showed that the subjects who have observed the expert's movements achieved higher performance than those without observation (Fig.3).

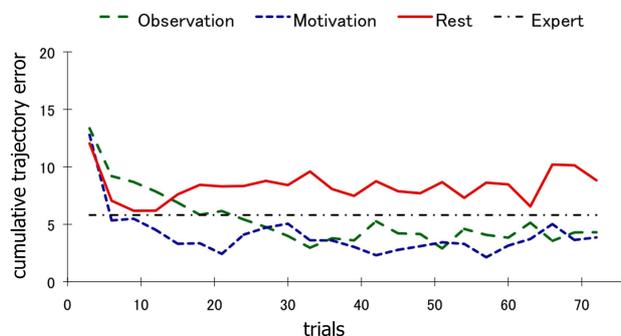


Fig. 3. Transition of cumulative trajectory error.

Moreover the subjects with motivated observation showed rapid performance improvement compared with those of non-motivated observation (Fig.4).

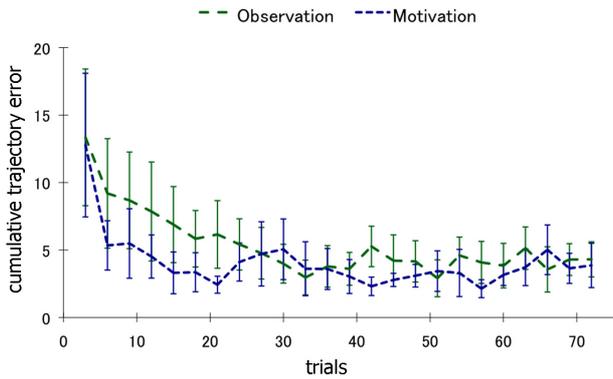


Fig. 4. Comparison of Observation and Motivation.

According to these experimental results, the subjects who experienced a preceding observation (i.e. Observation or Motivation group) outperformed the subjects without the experience (i.e. Rest). Seemingly it suggests that observing expert’s movement beforehand has a positive effect on the latter stage of the motor learning (i.e. final performance level). However in Matter’s experiment [4], there can not be confirmed any difference in the latter stage of the learning between the subjects with and without observation. One possibility is that our experiment did not give enough feedback of performance for the subjects to pursue improvement based solely on it.

On the other hand, we confirmed that the subjects in Motivation group demonstrated a rapid performance improvement (See Fig.4). Based on these results, it can be considered that the motivated observation would have a positive effect on the early stage of the motor learning in comparison with just looking. After each learning experiment, we have asked the subject who observed expert’s video (i.e. both Observation and Motivation groups) about what he had payed attention to during the observation. As a result, all subjects in the Motivation group reported that they had gazed at the curve of the cursor trajectory, while those of the Observation group was inconsistent (e.g. trying to find target emerging rule, seeing blankly, etc.). Thus it can be considered that the motivated observation played a role of making up the attitude for the motor learning by creating motor imagery.

#### IV. CONCLUSION

In this paper, we reported about two research topics of our group executed in the two years. The first one is the experiment concerning simultaneous learning of conflicting visuomotor rotations. We focused on the effect of successive experiences during the simultaneous learning process. It had been reported that simultaneous learning of two opposing force fields with a random order was better than alternating order, even if both have the same total number of experiences. We assumed this was because the alternating schedule gave no chance to retry the same rotational transformation successively. To evaluate this assumption, we compared three training conditions: alternating every trial, alternating every two trials,

and changed at random. Experimental results suggested that providing the chance of successive trials had a small positive effect on the simultaneous learning. However the subjects trained under the random condition still showed a significant advantage in comparison with those trained under the other conditions.

In addition, we investigated the effect of observing expert’s movement before motor learning. To make clear these experimentally, motor learning paradigm of arm reaching movement under viscous curl force field was adopted. As a result, it suggested that observing expert’s movement beforehand has a positive effect on the latter stage of the motor learning. Moreover we confirmed that motivating to observe an expert’s movement have a positive effect on the early stage of the motor learning. These results imply that not only focusing on the learning process of sensorimotor coordination, but also considering the intrinsic context (e.g. cognition, emotion, impulsion, etc.) and anticipation of external environments (i.e. somatosensory feedback) are significant in order to understand human motor learning.

#### REFERENCES

- [1] Krakauer, J. W., Ghilardi, M.-F. and Ghez, C. Independent learning of internal models for kinematic and dynamic control of reaching, *Nature neuroscience*, **2**, 11, 1026–1031, 1999.
- [2] Karniel, A. and Mussa-Ivaldi, F. A., *Sequence, time, or state representation: how does the motor control system adapt to variable environments?*, *Biological Cybernetics*, **89**, 1, pp.10–21, 2003.
- [3] Osu, R., Hirai, H., Yoshioka, T., and Kawato, M. Random presentation enables subjects to adapt to two opposing forces on the hand, *Nature neuroscience*, **7**, 111–112, 2004.
- [4] Matter, A. A. G., and Gribble, P. L. Motor learning by observing, *Neuron*, **46**, 156–160, 2005.
- [5] Gallese, V., Fadiga, L., Fogassi, L., and Rizzolatti, G. Action recognition in the premotor cortex, *Brain*, **119**, 593–609, 2006.
- [6] Rizzolatti, G., Fogassi, L., and Gallese, V. Mirrors in the Mind, *Scientific American Magazine*, 2006.
- [7] Calvo-Merino, B., Glaser, D. E., Grezes, J., Passingham, R. E., and Haggard, P. Action observation and acquired motor skills: an fMRI study with expert dancers, *Cerebral Cortex* **15**, 1243–1249, 2005.
- [8] Vogt, S., Buccino, G., Wohlschlaeger, A. M., Canessa, N., Shah, N. J., Zilles, K., Eickhoff, S. B., Freund, H.-J., Rizzolatti, G., and Fink, G. R. Prefrontal involvement in imitation learning of hand actions: Effects of practice and expertise, *NeuroImage*, **37**-4, 1371–1383, 2007.

# *Mobiligence* for optimal investment : toward the computational algorithm of instantaneous gain rate

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**Abstract**—Do animals have mind? Do non-mammalian vertebrate animals in particular have mental processes similar to ours? The issue of “animal mind” has long been unchallenged simply because it was ill-defined. Recent progresses in behavioral studies in birds, however, revealed that they have cognitive process analogous to ours. Basic assumption is that selection pressure has shaped economically rational (i.e., features linked to maximization of own benefit; or greedily ego-centric decision maker hypothesis) as evolutionary adaptive traits. Common selection pressure therefore could have shaped basically identical cognitive processes in taxonomically distinct groups of animals, such as mammals (including human) and birds. The evolutionary explanation will make sense, if animals show optimal behaviors in a variety of different situations. Guided by this strategy, in the term from 2006 through 2009, we have accomplished the following series of experimental studies. (1) We compared risk sensitivity in two distinct conditions; one in which the amount was at risk (i.e., the associated amount of food reward varied among trials) and another in which the proximity was at risk (i.e., the associated delay to the food reward varied among trials at equal probabilities). Chicks showed risk aversion in amount, and risk proneness in delay, in favor of the dissociated internal representation of amount and delay. In order to reveal the difference, however, we had to apply Bayesian estimation (or statistical analysis of behavioral data by using hierarchical Bayesian models). (2) Developmental facilitation of impulsiveness by competitive foraging was experimentally confirmed in behavioral titration experiment using inter-temporal choice paradigm. Social competition causes loss and risk of gain, however, both of these factors failed to enhance the impulsiveness. Instead, visual perception of competitive foragers proved to be sufficient. (3) In the condition where food was supplied without any immediate cues, social competitors caused an excessive labor investment (enhanced investment of locomotion) without experiencing actual loss of gains. (4) Patch use behavior was experimentally reproduced by using a feeder of gradually diminishing return. The mean residence time proved to follow Poisson process, whereas the underlying decision was based on retrospective time perception, or the interval of two successive food delivery in the immediate past, in a clear contrast to the binary choices that were based on anticipatory (prospective) sense of time. (5) Newly-hatched chicks (i.e., chicks without any visual experiences), once exposed to visual motion stimulus according to the “imprinting” procedure, proved to show strong preference to Johansson’s biological motion (BM). The development of the BM preference was sexually dimorphic, with stronger effects in males than in females. These results suggest (A) chicks are innately equipped with “template” for visual perception of other conspecifics, (B) and the template is induced by visual experiences, (C) thus causing an excessive labor investment as an immediate

consequence, and (D) causing an enhanced impulsiveness in the long run, therefore (E) allowing chicks to modify internal value function for decision making so that their gain rate would be meliorated in accord with individual socio-ecological condition.

## I. INTRODUCTION

RECENT progress in behavioral studies of birds suggested that they have cognitive processes analogous to ours, humans. Pepperberg [1] reported that African Grey Parrots are able to communicate with human in English (a natural language of *Homo*). Clayton [2] has studied food storing behaviors and assumed that blue jays (corvids in general) could have episodic-like memory. Furthermore, Emery [3] has suggested that jays organize their behaviors based on assumption of other individuals’ cognitive process, indicative of “theory of mind” in birds. All these cases were successful in showing that the birds have cognitive processes similar to primates. Does it mean that they have “mind” that is identical to ours?

This issue of the animal mind is however, terribly ill-defined, simply because many topics and concepts remain highly *polysemic*; without specifying them, we are unable to precisely argue the “similarity”. It is also highly controversial whether elementary brain processes in animals (and humans) mind process can be categorized in the same fashion. Purely materialistic approaches have limited applicability to the issue of mind.

In this report, I will introduce some of our recent experimental psychological studies on domestic chicks. The idea is that the neural and cognitive processes of foraging choice should be understood in a close relationship with their ecological backgrounds. Through viewing the issue in both ecology and neuroscience, we will be prepared to discuss the issue of animal mind (or evolution of intelligence) with minimal assumptions.

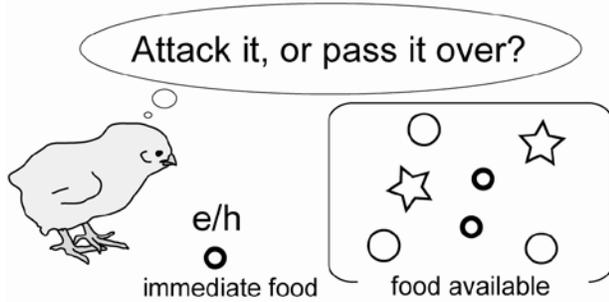
Due to phenomenal convergence, a given “equation” often yields a diverging spectrum of “solutions.” Neuroscience has been a powerful tool, because we could disregard those “solutions” that were physiologically unrealistic. Similarly, through filtering the possible “solutions” by ecological / evolutionary means, we will be given additional constraints, thus making our arguments on animal minds more tractable (i.e., requiring fewer lines of assumption) than it used to be. The present series of study thus aims at the foundation of *neuro-ecology*.

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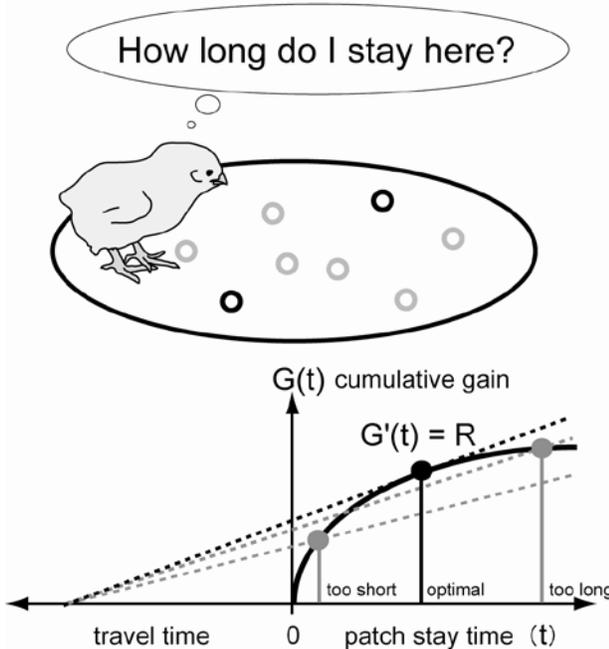
## II. FORAGING THEORY

Based on insect behaviors, Charnov [4] proposed two classical models for foraging behaviors based on foraging behaviors, both of which are quantitatively formulated and are highly sensitive to experimental verifications; they are, *optimal diet menu model* (or optimal prey menu model) and *optimal patch use model* (or optimal patch stay time model). Both of these two models assume that rational decision makers adopt the optimization strategy, so that animal behaviors are designed toward maximization of subjective long-term gain rate.

### A Optimal Diet Menu Model



### B Optimal Patch-use Model



**Fig.1 Optimal menu model (A) and patch-use model (B)**

**A:** Assume a forager that encounters one of  $n$  different kinds of food items. The forager decides to attack the food, or to pass it over in search for an alternative, or lost opportunity. **B:** Assume a situation in which food resources are unevenly scattered in a patchy manner, and the forager encounters one of these patches. As the forager continues to forage in the patch, naturally the resource will be exhausted, making the instantaneous gain rate gradually decrease. At a marginal point

( $G'(t)=R$ ), in which the instantaneous gain rate reaches maximum, optimal forager should leave the patch of food.

Natural condition is actually much more complicated than those assumed in these models. Food items are often scattered in a patchy fashion, and forager must move from a patch to another without explicit information on the location and quality of food patches. Once subject encounters a patch, he will collect the food items. In the initial phase of patch use, the gain rate is high, because the patch is fresh with a certain amount of food. Subsequently, as the forager stays longer, the food density decreases, making the instantaneous gain rate monotonically decreasing. Optimal forager must leave the patch before the food is exhausted. At certain point of time, the lost opportunity (the gain available in the next patch) will exceed the immediate gain, making the move an economically rational decision. The law of “diminishing return” holds true also in the animal economics.

Ecological / ethological studies in insects, birds and fish basically proved validity of these two models, as they are successful in predicting some of the foraging behaviors [5]. The *molar* properties of foraging behaviors thus follow general rules irrespective of evolutionary backgrounds. What behavior and cognition at the *molecular* level are responsible?

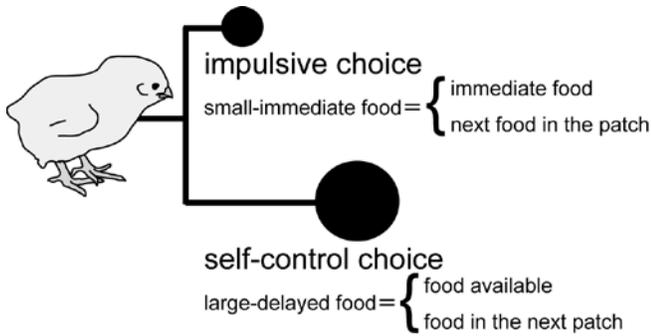
## III. CHOICE THEORY

Birds do not learn aerodynamics in order to fly. Similarly, economical decision makers do not need to learn economics in order to achieve the optimal foraging. The point is whether the decision leads to the long-term gain, irrespective of the immediate consequences.

It should be noted that both of these models could be explained by a unifying scheme as shown in **Fig.2**. Here, the choices are between “small-but-immediate reward” (immediate food or the food available within reach) and “large-but-delayed food” (lost opportunity). In psychological framework for human behaviors, the former is referred to as *impulsive*, while the latter *self-control*. Clearly in human society, we have an agreement that the self-control choice is “adaptive” and the impulsive choice is a “maladaptive” trait.

When viewed from the ecological standpoint, however, the terms seem somehow misleading. Actually, in many situations, foraging animals show a certain level of impulsiveness in foraging decisions, suggesting that the distance (spatial proximity) or delay (temporal proximity) is critical. Why?

Under natural condition, the immediate food is often available for a short period of time. The food item may flee, or snatched by others, making the self-control decision makers less profitable. In this situation, on the other hand, impulsive decision makers may even maximize the long-term gain rate. Depending on the food resources, level of impulsiveness must be appropriately kept elevated to a certain point.



**Fig.2 Inter-temporal choice scheme as a unifying framework for the two models of optimal foraging theory**

#### IV. RISK, UNCERTAINTY, AND COMPETITIVE SOCIETY

Expected gain of a food of amount  $A$  at probability  $p$  ( $<1$ ) is objectively given by the product  $p \cdot A$ . When  $p$  is known (or complete information is consistently available for  $p$ ), agent is supposed to face a risk. On the other hand, when the agent must explore  $p$ , and the information of the  $p$  value inevitably contains some sort of unreliability, the agent faces an uncertainty. Uncertainty arises either when the physical (or material) conditions vary in a manner unpredictable for the agent, or when social competitors interfere with the agent's foraging thus causing a "collection risk".

(1) As the first step, we examined risk sensitivity in chicks [10]. Profitability decreases either by a decrease in the amount of gain or by an increase in the delay (or handling time). Risk arises therefore either by a variable amount or by a variable delay. Behavioral study (behavioral titration technique) revealed that chicks show difference in their risk sensitivity in these two cases. Behavioral data were blurred by the high level of individual differences, and we adopted hierarchical Bayesian analysis for the study of subjective values to estimate subjective values of risky option at individual level, and found a consistent population-level tendency. Chicks were risk averse for the amount at risk, whereas they were risk prone when the delay was at risk. These results suggest that subjective value is not uniquely given as an integrated manner in the internal model for decision making.

(2) Interference by social competitors inevitably increases the uncertainty. We therefore examined the effects of social competition on the inter-temporal choices [11], and found that competition actually facilitated impulsiveness. Varying amount *per se* failed to cause a similar effect, even when the amount was controlled according to a Poisson process. On the other hand, presence of a "competitive forager" placed in the other side of the separated chambers was similarly effective as those placed together, thus suggesting that perceived competition was sufficient without actual loss and risk of the

gain. An increase in the impulsiveness may enable chicks to secure minimal amount of food under competition, thus rescuing them from death by starvation. In other words, competition could make the impulsiveness an adaptive trait.

(3) We also examined behavioral effect of social competition on the labor investment in the foraging context [12]. A pair of experimental feeders was connected via a runway, thus forming an I-shaped maze. Each of the feeders independently supplied a grain of millet at a time, and the interval was set according to a pseudo-Poisson distribution. Chicks in this experimental setup automatically learned to shuttle between the two feeders, and the labor investment measured in terms of the number of shuttle per min exceeded the level at which the subject chick gained the grain as soon as a grain was served. Chicks ran too much. When a pair of chicks was tested in the maze, both chicks showed a further excessive investment by increasing the running speed. Shuttles of these chicks were highly synchronized, and the trajectories were analogous to those of coupled non-linear oscillators. As the trials were repeated, frequency of "coupled" shuttles gradually decreased and in-phase synchronization was often replaced by anti-phase synchronization. Separation of foraging chicks by using a transparent wall (therefore the actual gain loss was not caused by the competition; so-called perceived competition), such an anti-phase synchronization did not develop. These results suggest that the primary behavioral effect of social competition could be an increase in the behavioral investment to gain a certain amount of food, which secondarily enhance the impulsiveness.

(4) We analyzed chicks decision to leave a food patch of diminishing gain rate [13]. The stay time (or the period of time until the foraging chick left the patch) was approximated by a gamma distribution, suggesting that the chicks have only the "leave" probability. The decision to leave was not determined by the prospective time until the next food will be served, thus that the decisions were not prospective. Furthermore, SSRI (serotonin-selective reuptake inhibitor) had systemic effects on behavior in a manner contrary to those expected by the unified theory of decision as discussed above in Fig. 2. The SSRI treatment increased the stay time, while the same chicks showed a suppressed impulsiveness. Decision to leave a food patch should be accomplished by distinct neuro-cognitive mechanisms from those involved in the inter-temporal choices.

(5) In order to specify the visual cues responsible for chicks to detect social competitors, we studied chicks' ability to discriminate [14]. Newly hatched chicks were examined in an arena equipped with a pair of computer monitors, each of which showed a motion picture composed of finite (up to 14) yellow dots on a black screen. In particular, effect of "imprinting" procedures was examined in the chicks' preference to Johansson's biological motion (BM). Even

when exposed (“imprinted” to) a motion picture composed of randomly moving dots, chicks developed a strong preference to BM stimulus (“walking hen”) over non-BM stimulus (“rotating hen”). The inductive effects of motion picture was evident particularly in males, and chicks that had been “induced” by a random motion picture showed a BM preference for hen-like object over cat-like object suggesting that chicks discriminated predators by BM. Most probable interpretation of the present results is that chicks have innate template for mother hens, and the preference is induced through early experience of motion picture.

## V. CONCLUSIONS

1. Classical foraging theory has proposed two different models, “optimal diet menu model” and “optimal patch use model”. These two models can be unified, as a single scheme of inter-temporal choice could explain these two. Results of behavioral and psychopharmacological studies were not in concert with the idea of unified theory.
2. It is suggested that the menu model is based on the anticipation of immediate future reward (or the prospective time perception), whereas the patch use model is based on the experience in the immediate past (or the retrospective time perception).
3. Results of the behavioral studies under risk and uncertainty are compatible with the idea that elements of values (such as amount, proximity, cost and probability) are multiply and separately represented. In particular, perception of social competitors could cause immediate increase in the labor investment, which could secondarily lead to an enhanced development of impulsiveness. Chicks have innate template for social perception by detecting biological motion of conspecifics, which however needs to be post-natally induced through visual experiences.
4. These results are not compatible with the idea that chicks are greedily optimal machinery for foraging food. Rather, chicks are equipped with behavioral traits to adapt to the given socio-ecological condition through the course of evolution.

## REFERENCES

- [1] Pepperberg, I.M. *The Alex Studies*. Cambridge, Massachusetts: Harvard University Press, 1999.
- [2] Clayton, N. & Dickinson, A. Episodic-like memory during cache recovery by scrub jays. *Nature*, 395, 272-274, 1998.
- [3] Emery, H.J. & Clayton, N. Effects of experience and social context on prospective caching strategies by scrub jays. *Nature*, 414, 443-446, 2001.
- [4] Charnov, E.L. Optimal foraging: the marginal value theorem. *Theoretical Population Biology*, 9, 129-136, 1976.
- [5] Stephens, D.W. & Krebs, J.R. *Foraging Theory*. Princeton, New Jersey: Princeton University Press. 1986.
- [6] Mazur, J.E. *Learning and memory* (5<sup>th</sup> ed.). Prentice Hall. 2002.
- [7] Matsushima, T. *et al.* Neuro-economics in chicks: foraging choices based on delay, cost and risk. *Brain Research Bulletin*, 76: 245-252, 2008.
- [8] Izawa, E.-I. *et al.* Localized lesion of caudal part of lobus parolfactorius caused impulsive choice in the domestic chick: evolutionarily conserved function of ventral striatum. *Journal of Neuroscience* 23: 1894-1902, 2003.
- [9] Ichikawa, Y. *et al.* Excitotoxic lesions of the medial striatum delay extinction of a reinforcement color discrimination operant task in domestic chicks; a functional role of reward anticipation. *Cognitive Brain Research*, 22: 76-83. 2004
- [10] Kawamori, A., Matsushima T. (2009) Subjective value of risky foods for individual domestic chicks: a hierarchical Bayesian model. *Animal Cognition* (DOI 10.1007/s10071-009-0293-1, online)
- [11] Amita, H., Kawamori, A., Matsushima T. (2009) Social influences of competition on impulsive choices in domestic chicks. *Biology Letters*. (DOI:10.1098/rsbl.2009.0748, on line)
- [12] Ogura, Y., Matsushima, T. Competitive foraging causes an excessive increase in locomotor activity in domestic chicks. Symposium on Brain and Mind (the 10<sup>th</sup> winter workshop Rusutsu, Rusutsu Jan., 2010)
- [13] Matsunami, S., Amita, H., Izumi, T., Yoshioka, M., Matsushima, T. Behavioral and pharmacological effects of fluvoxamine (SSRI) on inter-temporal choices and residence time of diminishing food patch in domestic chicks. (submitted)
- [14] Miura, M., Vallortigara, G., Regolin, L., Matsushima, T. Visual experiences enhances innate preference for BM in newly-hatched domestic chicks. Symposium on Brain and Mind (the 10<sup>th</sup> winter workshop Rusutsu, Rusutsu Jan., 2010)

# Recalibration of time to contact

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**Abstract**—In order to elucidate the mechanism of predicting the timing of contact. We examined an experimental investigation of the adaptation process that shifts in the timing of the visual and tactile. Visual stimulus was the falling ball in  $9.8 \text{ m/s}^2$  acceleration for any tactile stimuli and the tactile stimuli was shifted 60 msec. The subject repeated the ball catch task with shifted condition. As a result, the subjects did not aware the timing shift, but they change the timing of tactile contact with the estimated time. This means that the simultaneity was also shifted about 60 msec after the adaptation task.

## I. INTRODUCTION

We are born without adapting to the natural environment on Earth, and have been adapting to the environment by learning. To recognize the environment, especially visually, its color, shape and texture as well as external features, or to study the physical characteristics such as weight and softness. This capability not only be acquired by sight, touch and manipulation of the object give us some information about the dynamics of it. To manipulate the object, brain needs to generate a motor command to control the movement of arms. Moreover, the brain can estimates the future state[5]

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The pathway of two cortical systems provide 'vision for action' and 'vision for perception', respectively [4].

We can assume two hypotheses for explaining this phenomena in fig. ?? . One is that the subject learned the different timing by using visual stimuli (1). They would become to estimate the different TTC with same visual stimuli as they learned the different acceleration. The other one is that the subject learned the delay between the motor command and muscle tension (2). It is known that the delay between muscle activation and force exertion is about 100 msec, and the delay between motor cortex and muscle is about 20 msec. Usually, we don't aware of this delays during motor tasks. We probably learned this delay and send the motor command beforehand to compensate these delay.

There are some researches which has been focused on the sense of the time difference between two modalities in both physical transmission time and sensory processing time. Visual signals to reach the brain behind times, so the scene what we are looking now is in the past[1]. However, for a variety of different sense of time delay, some mechanism is needed to ignore it[2]. Thus, the time difference between the auditory and visual are investigated. In this study, the time

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difference between visual and tactile were examined. Also the stimuli was not passive.

## II. METHOD

### A. VR environment

We use a haptic device "SPIDAR" which use four motors (Maxon DC motor, RE25) to strain by strings for applying the force to a hand [3]. This device can be measure the position by measuring the length of the strings by rotary encoder in 1 kHz sampling.

We also measure Electromyographic (EMG) signals (Bagnoli-16 system Delsys inc.) for measuring a intention for catching, because EMG signals activate about 100 msec before exerting a force. Active electrode was put on palmaris longus and EMG signals was sampled at 2 kHz with 16bit. In order to show the visual stimuli to the subject, plasma display (PDP503-CMX, 50 inches, Pioneer) was used. Virtual ball was falling from 80 [cm] height with 0 [m/sec] initial velocity, was same color and size, and applied 4.9 [N] force to right hand for 1.1 sec for different perturbation conditions.

## III. EXPERIMENT

### A. Subjects

3 healthy subjects ( 3 men, 23 ~ 29 years old) participated in the study. The subjects were right-handed, had normal vision or vision that was corrected for normal. Experiments were conformed to the Declaration of Helsinki on the use of human subjects in research.

### B. Visual and haptic display using virtual reality environment

Figure 1 shows a experimental environment. We use a haptic device "SPIDAR" which use four motors ⊗⊗ axon DC motor, RE25) to strain by strings for applying the force to a hand [3]. We also measure Electromyographic (EMG) signals (Bagnoli-16 system Delsys inc.) for measuring a intention for catching, because EMG signals activate about 100 msec before exerting a force. Active electrode was put on palmaris longus and EMG signals was sampled at 2 kHz with 16bit. In order to show the visual stimuli to the subject, plasma display (PDP503-CMX, 50 inches, Pioneer) was used. Virtual ball was falling from 80 [cm] height with 0 [m/sec] initial velocity, was same color and size, and applied 4.9 [N] force to right hand for 1.1 sec for different perturbation conditions.



Fig. 1. Experimental environment.

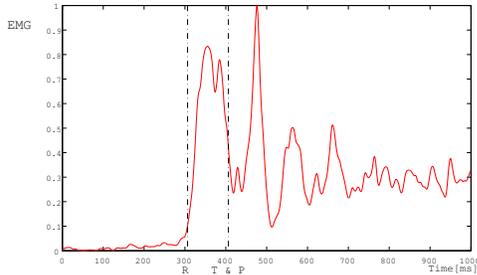


Fig. 2. Average onset timing of EMG signals as a function of repetition for each condition

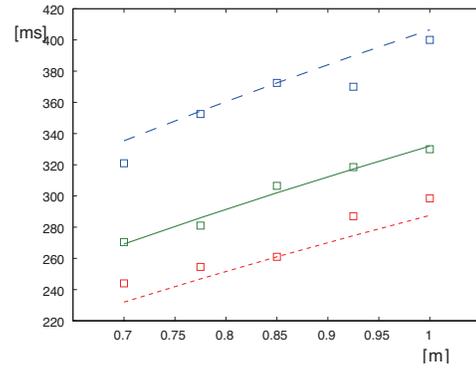
### C. Experimental procedure

Subjects were asked to catch the ball at the initial position. At the beginning of the trial, beep signal sounded and after a random delay ranging from 0.75 to 1.25 sec, the virtual ball was falling with 0 m/s initial velocity and  $9.8 \text{ m/s}^2$  acceleration.

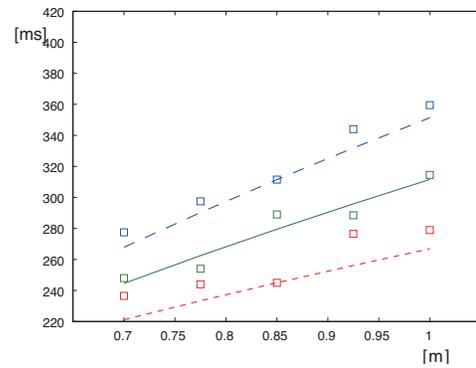
Subjects performed 3 different experiments. In each experiment, the force timing and the drop altitude was different, and the timing was selected from 3 conditions, -60, 0, 60 [msec] and the height was selected from 5 conditions, 70.0, 77.5, 82.5, 85.0, 100 [cm].

## IV. RESULTS

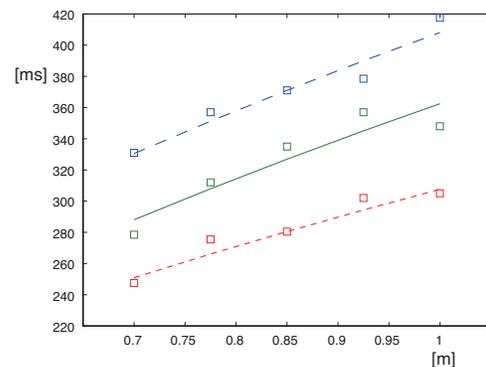
Figure 2 shows the average rectified EMG signals and low-pass filtered EMG signals with 50 Hz cut off frequency. The time when the force was applied to the hand was shown as dotted vertical line (indicated “T and P”). In each delay condition, EMG activities became to increased 100 msec before applying the force (indicated “R”).



(a) subject A



(b) subject B



(c) subject C

Fig. 3. EMG onset timing for different height conditions

Figure 3 shows the EMG onset at the different height conditions. The estimated acceleration was  $9.65[\text{m/sec}^2]$  (solid line) ,  $16.60[\text{m/sec}^2]$  (dotted line) and  $8.87[\text{m/sec}^2]$

(dashed line) for  $\pm 0$ ,  $-60$  and  $+60$  conditions respectively. The average acceleration for 3 subjects was 11.71, 18.70 and 8.56 for  $\pm 0$ ,  $-60$  and  $+60$  conditions respectively. The theoretical value of acceleration is  $13.38[\text{m}/\text{sec}^2]$  and  $7.49[\text{m}/\text{sec}^2]$  for  $-60$  and  $+60$  conditions.

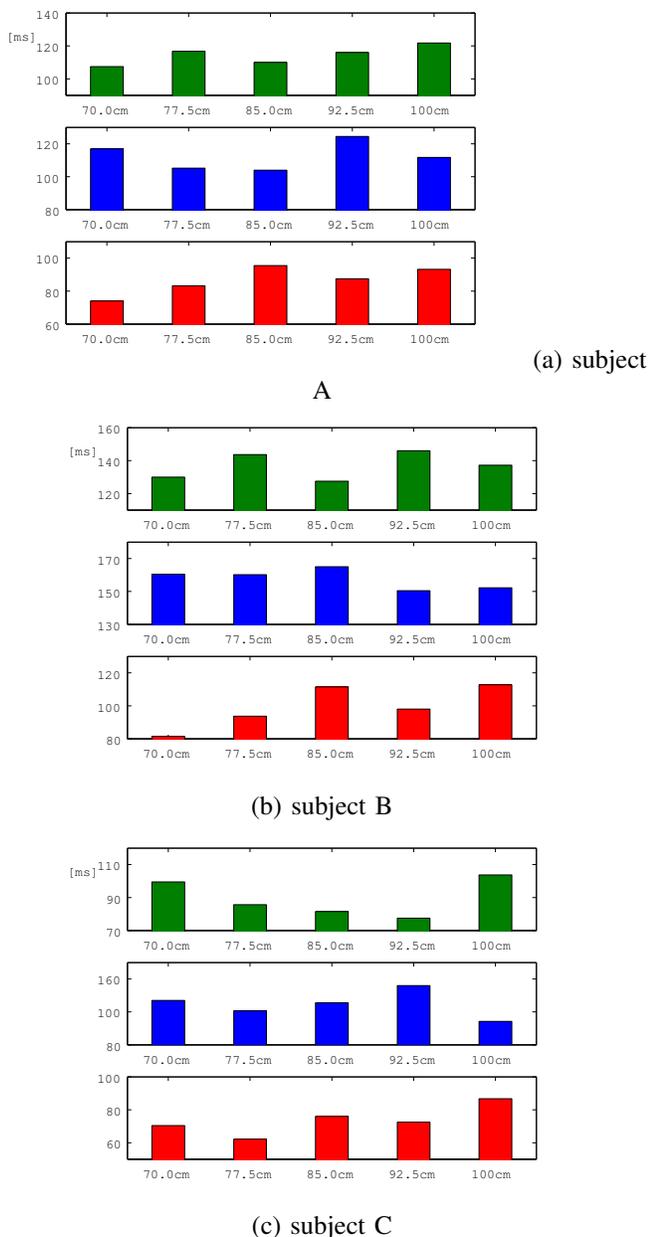


Fig. 4. Time difference for different height conditions

Figure 4 shows the time difference between EMG onset and force onset. At the 85cm height conditions, the subjects learned the different timing and the difference were about 100 msec. In the condition  $\pm 0$ , the time difference were almost 100 msec. In the condition  $-60$  and  $60$  msec, the time difference were not equal comparing to the  $\pm 0$  condition.

### A. Ball catching task

Subjects were asked to catch the ball at the initial position. At the beginning of the trial, beep signal sounded and after a random delay ranging from 2.5 to 3.5 sec, the virtual ball was falling with 0 m/s initial velocity and  $9.8 \text{ m}/\text{s}^2$  acceleration.

In experiment 1, the participants judged the simultaneity of vision and haptic stimuli presented with various time lag from  $-200$  msec to  $200$  msec. One condition was that the visual stimuli was fixed to  $9.8 \text{ m}/\text{s}^2$  and the haptic stimuli was shifted from  $-200$  ms to  $200$  ms randomly. Other condition was that the haptic stimuli was fixed to  $9.8 \text{ m}/\text{s}^2$  condition (about 400 ms) and the vision stimuli was changed from about  $4.4 \text{ m}/\text{s}^2$  to  $20.0 \text{ m}/\text{s}^2$ . A trial consisted of pairs of stimuli presented at one of 15 physical stimuli onset asynchronies (SOA), which were randomly interleaved within a method of constant stimuli. In this study, positive SOAs always refer to a visual lead and negative always to a tactile lead. Each experiment contained 20 presentations at each SOA.

In experiment 2, subjects performed two different experiments. In each experiment, the force timing was different, and the timing was selected from 2 conditions,  $-60$  or  $60$  msec. In  $60$  msec delayed condition, the force signal was applied after  $60$  msec in visually contact.

Subject caught the ball with constant time lag condition and repeated 100 trials for adaptation without any judgment.

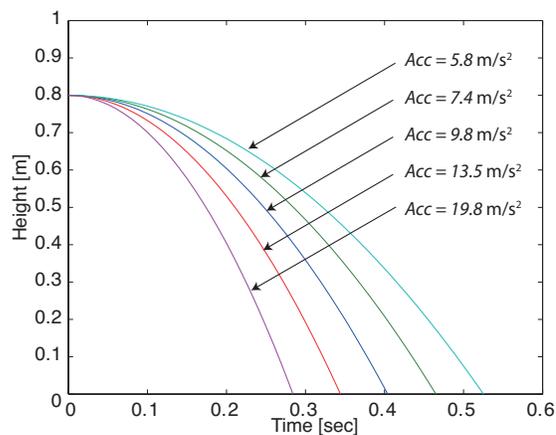


Fig. 5. Ball trajectories for different acc conditions.

After the adaptation phase, the subject did the same experiment for time lag judgment as same as experiment 1. In the experiment, the subject made an unspeeded temporal order judgment task as to “which stimuli came first.” The subject was forced to choose the tactile or the vision stimulus which was preceded.

## V. RESULT

### A. Experiment 1

In experiment 1, the subject performed two different conditions. The vision stimuli was the ball trajectory of  $9.8$

$m/s^2$  acceleration and the tactile stimuli was shifted from -200 to 200 ms (blue dot). Other condition was the tactile stimuli was constant at  $9.8 m/s^2$  acceleration timing. The vision stimuli was shifted from  $6 m/s^2$  to  $20 m/s^2$  (red dot).

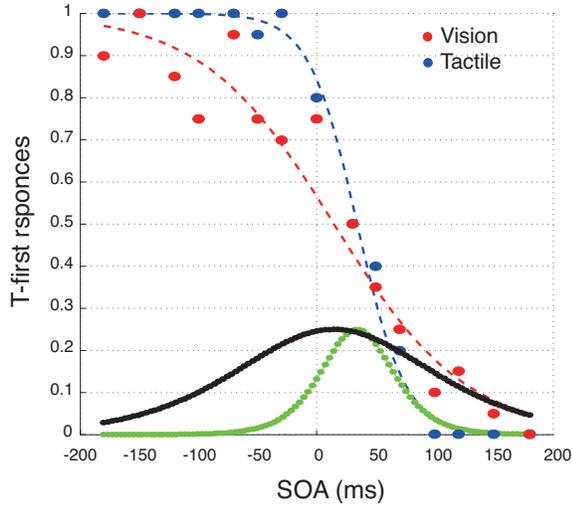


Fig. 6. Psychometric functions for visuotactile pairing

Psychometric functions can be seen in Fig. 6. The corresponding to the 50% response level on the psychometric function was about 30 msec and the sensitivity of SOA was height for tactile condition. This because that it is difficult to judge the difference of visual stimuli and the subject would estimate the same timing as  $9.8 m/s^2$  conditions.

### B. Experiment 2

In experiment 2, after the adaptation, the vision stimuli was the ball trajectory of  $9.8 m/s^2$  acceleration and the tactile stimuli was shifted from -200 to 200 ms in Fig. 7 (red dot).

As a result, the simultaneity was also shifted to about 60 msec and it was the same time lag of the adaptation. From previous some experiments, we found that the onset of EMG activities before the time to contact. So motor planing or the state estimation of the ball was affected and also the judgement was shifted.

## VI. CONCLUSION

Visual stimulus was followed the normal gravitational environment and only the timing of force was changed. In this condition, the subjects could learn the proper timing of catching task. This means that the subject predict the timing of contact from the adaptation task. Also the subject shifted the simultaneity of vision and tactile stimuli.

Moreover the subject could adjust the timing of not only the static tactile environment, but also dynamic environment such as ball catching task.

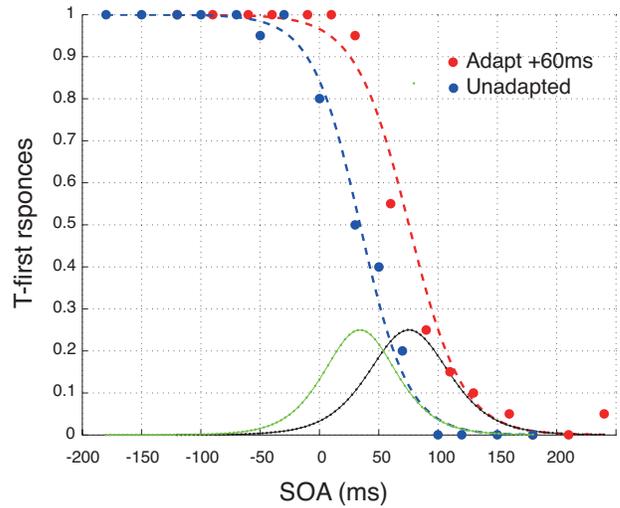


Fig. 7. Psychometric functions after adaptation

## REFERENCES

- [1] W. Bair, J.R. Cavanaugh, M.A. Smith, and J.A. Movshon. The timing of response onset and offset in macaque visual neurons. *J Neurosci*, 22(8):3189–205, 2002.
- [2] W. Fujisaki, S. Shimojo, M. Kashino, and S. Nishida. Recalibration of audiovisual simultaneity. *Nat Neurosci*, 7(7):773–8, 2004.
- [3] Masahiro Ishii and Makoto Sato. A 3d spatial interface device using tensed strings. *Presence*, 3:81–86, 1994.
- [4] A.D. Milner and M.A. Goodale. Two visual systems re-viewed. *Neuropsychologia*, 46(3):774–85, 2008.
- [5] Miall Wolpert. Forward models for physiological motor control. *Neural Netw*, 9(8):1265–1279, 1996.

# Neural mechanisms underlying knowledge-based learning with trial-and-error behaviors in the macaque prefrontal cortex

Atsushi Fujimoto, Tomohiro Tanaka and Tadashi Ogawa

**Abstract**—Facing an unknown problem, human and animals can provide appropriate responses by learning new knowledge to link relevant sensory stimuli to arbitrarily goal-directed actions. For the formation of such an intellectual, knowledge-base learning, the repetition of trial-and-error behaviors and their outcomes are essential. To elucidate underlying neural mechanisms in the lateral prefrontal cortex (LPFC), we examined the activity of LPF neurons when a monkey learned new task-relevant knowledge through trial-and-error behaviors. We found that the activity of some LPF neurons greatly varied between the initial trial-and-error period (error trials before the 1st success trial after a task-rule switch) and the following maintenance period (success and ordinary error trials after the 1st success trial), suggesting that LPF neurons can be a high-level observer for an intellectual, knowledge-base learning.

## 1. INTRODUCTION

The cognitive ability to construct appropriate solutions to unknown problems is essential for survival. Even in facing an unknown problem, human and animals can give appropriate responses. In problem solving, a trial-and-error method is essential and plays a key role. Even when there is no information about the solution of a given problem, we can choose one possible answer and apply it to the problem. If it were not successful, we would choose another answer and test it. We will repeat such a trial-and-error behavior until the selected answer yields an appropriate solution. Through such trial-and error behaviors, we obtain new knowledge about which sensory signals was task-relevant and how to link them to arbitrary actions in solving an unknown problem.

It has been thought that the lateral prefrontal cortex (LPFC) is central to such a knowledge-base learning with trial-and-error behaviors. Single-unit studies have shown that neurons in the LPFC exhibit rule-specific activity. Sakagami and Niki (1994a, b) recorded single-unit activity from the inferior dorsolateral prefrontal cortex (DLPFC) of monkeys performing a go/no-go discrimination task in which they had to base their response on the color, or the shape, or the position of a cue. The effect of changing the relevant sensory signals on neuronal responses to the discriminative cue was analyzed.

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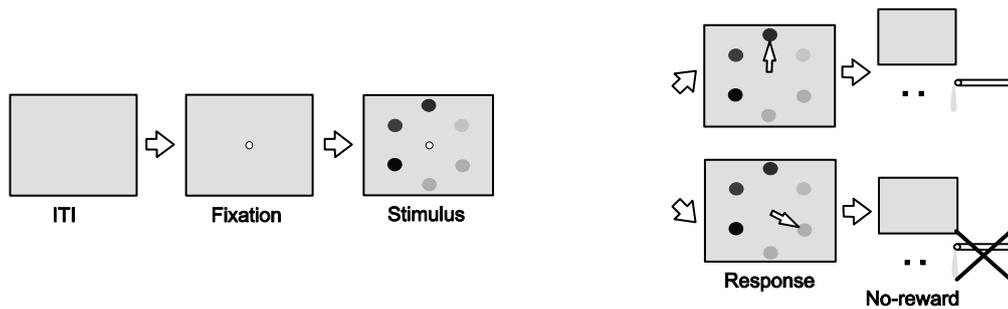
Some neurons in the dorsolateral prefrontal cortex displayed condition-dependent anticipatory activity prior to the cue onset, suggesting that neurons in the inferior DLPFC may participate in the conversion of sensory information from different stimulus features into arbitrary actions [1, 2]. Another study demonstrated that neuronal activity in the LPFC involved in the process of motor selection in accordance with two behavioral rules (location-matching task vs. shape-matching task)[3]. Further, to examine the ability to abstract principles or rules from direct experience, which may allow behavior to extend beyond specific circumstances to general situations, Wallis et al. (2001) explored the neuronal activity in the LPFC of monkeys performing a task based on two abstract rules in which the monkeys were required to indicate whether two successively presented pictures were the same or different depending on which rule was currently in effect. They found that most prevalent neuronal activity observed in the PFC reflected the coding of these abstract rules [4].

Thus, the previous studies suggested that LPFC is central to the ability to flexibly form principles or rules from direct experience (knowledge-base learning). However, because these studies examined the neuronal activity only after subjects (monkeys) fully learned the rules to execute the task. Even in a recent study that made experiments using a Wisconsin Card Sorting Test (WCST) in which the relevant rule and its changes were not cued, monkeys were able to know the relevant rule immediately after they had made one error trial (no trial-and-error behaviors), because there were only two available rules in the task [5]. Hence, how the LPFC contribute to rule-abstraction or knowledge-base learning through the repetition of trial-and-error behaviors remains unclear. To assess this issue, we explored the activity in the LPFC of a macaque monkey performing a visual search task in which the monkey should search for the relevant target-color with the repetition of a trial-and-error behavior and its outcome. The present results suggest that LPF neurons can be a high-level observer in a knowledge-base learning process.

## 2. METHODS

One Japanese macaque monkey (*Macaca fuscata*) was used in this study. A recording chamber was placed at stereotaxic coordinates over the lateral prefrontal cortex and anchored flat against the skull.

The monkey was required to perform a visual search task in which the target was defined by color feature



(Fig. 1). An array of six stimuli appeared on an imaginary circle around a central fixation point. Individual stimuli had different colors (red, orange, yellow, green, blue, and pink). The target color was randomly selected from the six colors at the start of every trial block and it was maintained in a trial block (20-80 trials). Because the monkey was not explicitly informed about the target color, it should search for the relevant color with the repetition of a trial-and-error behavior and its outcome after each of the target-color switches. So, we called the present task as *trial-and-error visual search task*. When the monkey made a single saccade to the target, a high-tone sound pulse was delivered and it received liquid reward (success trial). When the monkey made a saccade to the other stimulus, a low-tone sound pulse was delivered and it received no reward (error trial). If the gaze deviated from the fixation window before the fixation offset, the trial was aborted without any sound and reward.

前頭前野外側部 Eye position was monitored and recorded at 1 kHz using the scleral search coil technique and extracellular activity was recorded and stored on a

computer at a sampling rate of 25 kHz in the trial-and-error visual search task [6-8].

### 3. RESULTS

#### *Behavioral performance in the trial-and-error visual search task*

The monkeys' behavioral performances during the trial-and-error visual search task were well above the chance level ( $1/6 = 16.7\%$ ). The average performance score was more than 80 % (88.8%) during the recordings sessions. Figure 2 illustrates an example of the behavioral responses in a session of the trial-and-error visual search task. Each row indicates the one trial-block in which the target-color was constant. Because the monkey was not informed about the target color after each of the target-color switches, it made multiple error trials before it made the 1<sup>st</sup> success trial (1-7 error trials, gray rectangles; trial-and-error period). Even though the monkey had no information about the relevant color during the trial-and-error periods, it kept executing the trial tasks and searching for the relevant color. Thus, we successfully trained the monkey to

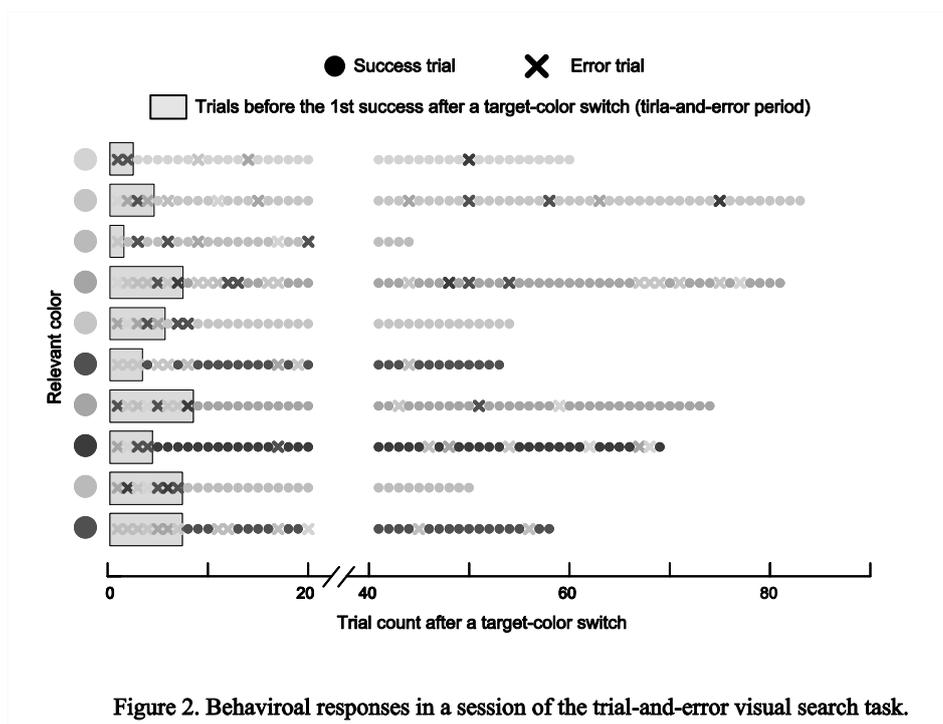


Figure 2. Behavioral responses in a session of the trial-and-error visual search task.

repeatedly execute trial-and-error behaviors after each of the rule switches (target-color changes). To quantitatively assess how the monkey detected a relevant color after a target-color switch, the percentages of correct responses were separately calculated for every trial after a color switch. Then, the mean correct performance after a color switch was calculated by averaging them across the trial blocks (Fig.

1<sup>st</sup> correct trials. These results suggest that the developments in the behavioral performance in each of the trial blocks may be not due to implicit learning (such as priming or perceptual learning), which might induce gradual increases in the correct performance, but due to explicit, knowledge-based learning, which might induce step-like changes in the correct performance as shown in Fig. 3B.

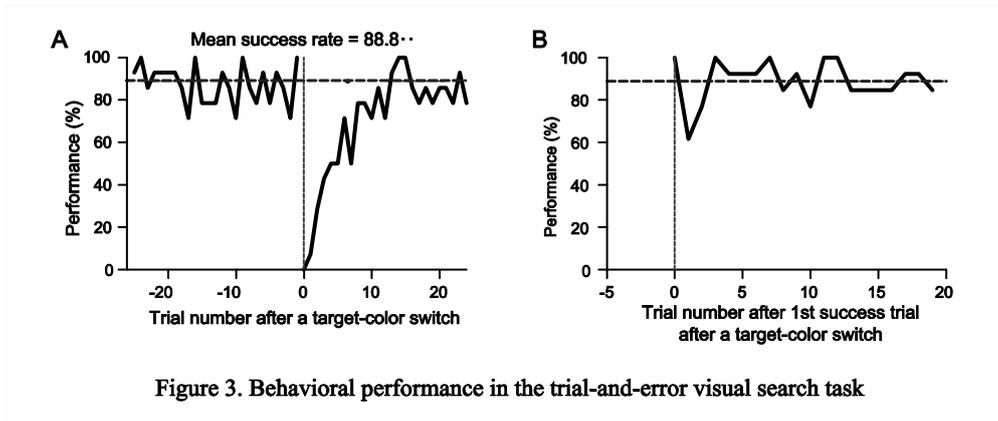


Figure 3. Behavioral performance in the trial-and-error visual search task

3A). The mean correct performance demonstrated gradual increase within the first ~15 trials after a target-color switch. But this does not indicate that the performance gradually developed in the individual trials. In a few or several trials after a target-color switch, the monkey made multiple errors before it made the 1<sup>st</sup> success in the visual search, as shown in Fig. 2. So, the performance in the first several trials maintained at low and almost at the chance level ( $1/6 = 16.7\%$ ). But once the monkey made the 1-3 success trials (typically, one success trial), the correct performance suddenly increased up to almost 90 % in a step-like manner and this high correct performance was maintained until the end of the trial blocks. Such a step-like change in the correct performance is well demonstrated in Fig. 3B which illustrates the correct performance aligned at the

#### Activity of a LPF neuron in the trial-and-error visual search task

Some LPF neurons showed increased or decreased activity specifically in the trial-and-error state (error trials before the 1<sup>st</sup> success trial after a target-color switch) comparing with that in the maintenance state (success or ordinary error trials after the 1<sup>st</sup> success trial). Figure 4 shows one representative neuron (eye position, rasters, and spike density functions from the top to the bottom). In the trial-and-error visual search task, this neuron activated tonically throughout a trial. Interestingly, the response patterns elicited in this neuron varied greatly between the trial-and-error state (black ticks in rasters and black trace in spike density functions) and the maintenance state (success and

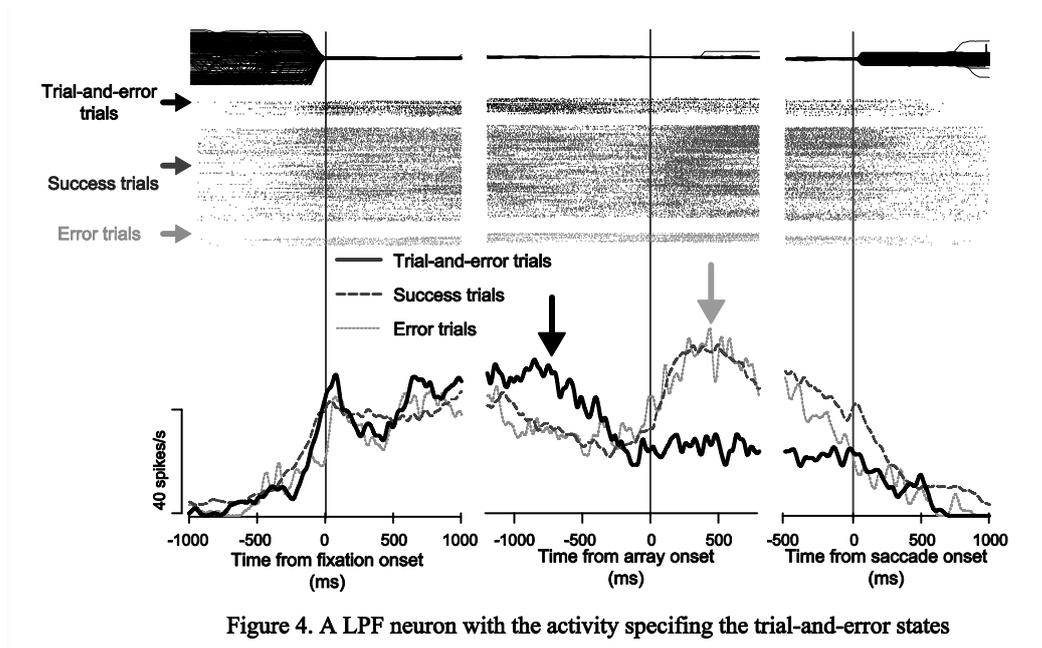


Figure 4. A LPF neuron with the activity specifying the trial-and-error states

ordinary error trials; dark and blight gray ticks and traces, respectively). The activity during the period from around 1000 ms to 500 ms before the array onset (black arrow) was stronger in the trial-and-error state than in the maintenance state. By contrast, the activity during the period ranged from the array onset to the saccade initiation (gray arrow) was stronger in the maintenance state than in the trial-and-error state. Thus, only the activity in the trial-and-error trials was substantially different from that in the other trials (success trials and ordinary error trials). Further, the trial state that induced the largest activity was alternated from the trial-and-error state to the maintenance state depending on the task event change (search array presentation).

It was unlikely that this differential activity was explained simply by the motivation (or the expected reward size that would be delivered at the end of the trial) because of the following two reasons. First, previous studies frequently reported that motivational depression often results in error trials. However, the present results demonstrated that the magnitude of the success and ordinary error trials were almost the same. So it was unlikely that general motivation for executing the current task was reflected in the activity of this neuron. Second, the trial state exhibited the largest activity was changed from the trial-and-error state to the maintenance state locked at the array presentation. So, it was unlikely that such a dynamical activity change in a trial was caused by general motivation of the subject.

These results illustrate that LPF neurons can discriminate the distinctive two conditions in the formation of an intellectual learning (trial-and-error condition vs. maintenance condition).

#### 4. DISCUSSION

We developed a new cognitive behavioral task (**trial-and-error learning task**) for monkey to investigate neural substrates underlying trial-and-error forming an intellectual learning. We successfully trained one monkey to perform well this task. Behavioral data demonstrated that performance score increased in a step-like manner after one or a few success trials after a task-rule switch (target color change), suggesting that the explicit, knowledge-base learning occurred through the trial-and-error behaviors after each of the task-rule changes. Consistent with this view, some neurons in the lateral prefrontal cortex demonstrated the distinctively different activities between the trial-and-error state (error trials before the 1<sup>st</sup> success trial after a task-rule switch) and the maintenance state (success or ordinary error trials after the 1<sup>st</sup> success trial). This difference in the prefrontal activity might reflect the distinctive two states in the formation of an intellectual learning: **unknown state (trial-and-error state)** in which the relevant sensory information (target color) is unknown and **known state (maintenance state)** in which the relevant sensory information is known. Thus, the present findings

suggest that LPF neurons can be a high-level observer for an intellectual, knowledge-base learning.

#### 5. REFERENCES

1. Sakagami, M. and H. Niki, *Spatial selectivity of go no-go neurons in monkey prefrontal cortex*. Experimental Brain Research, 1994. **100**(1): p. 165-169.
2. Sakagami, M. and H. Niki, *Encoding of behavioral significance of visual-stimuli by primate prefrontal neurons - Relation to relevant task condition*. Experimental Brain Research, 1994. **97**(3): p. 423-436.
3. Hoshi, E., K. Shima, and J. Tanji, *Neuronal activity in the primate prefrontal cortex in the process of motor selection based on two behavioral rules*. J Neurophysiol, 2000. **83**(4): p. 2355-73.
4. Wallis, J.D., K.C. Anderson, and E.K. Miller, *Single neurons in prefrontal cortex encode abstract rules*. Nature, 2001. **411**(6840): p. 953-6.
5. Mansouri, F.A., K. Matsumoto, and K. Tanaka, *Prefrontal cell activities related to monkeys' success and failure in adapting to rule changes in a Wisconsin Card Sorting Test analog*. J Neurosci, 2006. **26**(10): p. 2745-56.
6. Ogawa, T. and H. Komatsu, *Target selection in area V4 during a multidimensional visual search task*. J Neurosci, 2004. **24**(28): p. 6371-82.
7. Ogawa, T. and H. Komatsu, *Neuronal dynamics of bottom-up and top-down processes in area V4 of macaque monkeys performing a visual search*. Exp Brain Res, 2006. **173**(1): p. 1-13.
8. Ogawa, T. and H. Komatsu, *Condition-dependent and condition-independent target selection in the macaque posterior parietal cortex*. J Neurophysiol, 2009. **101**(2): p. 721-36.

# Study of Optimization of Cooperative Adaptation between Two Persons by Mutual Tracking Experiments

SAWADA, Yasuji and HAYASHI, Yoshikatsu

**Abstract**—A series of mutual tracking experiments verified that optimization of cooperative adaptation for the motional communication is realized by creating a common rhythm, whenever possible, and thereby reducing the fluctuation of the relative position between the two persons.

## I. INTRODUCTION

Verbal communication used in talks, letters, telephone calls and e-mails is a communication method by which people can exchange deeply cultural information. But it is not real time communication in exact sense, because one must wait a certain period of time before the other finishes a sentence. On the other hand, non-verbal communication using facial expression or body motion can be more instantaneous. We intended to study the condition for the successful motional communication, because the motional function was preferentially developed in the brain of animals in the early stage of evolution and because motional communication is easier to study quantitatively compared with the verbal communication.

## II. BACKGROUND

We have carried out visual hand-tracking experiments to study response of human control to the changing environment[1][2][3]. The subjects were asked to track the motion of a target as accurate as possible in the screen of a computer. The results are summarized as;

- 1) The function of position error correction and the function of predictive tracking do operate mutually exclusively and not simultaneously in human visual-motion system.
- 2) When the target moves quickly, the brain takes in target information only intermittently, as the processing of all time information is too heavy. During the time interval in which target information is not used, the internal image of the target information moves faster (internal clock moves faster than the physical clock). On the other hand, during the time interval in which target information is used, the internal image of the target is controlled to move with the same speed with the target (internal clock coincides with the physical clock). The hand motion as the average moves proactively to the target.
- 3) This proactivity based on the predictive mechanism is consistent with the evolution of animals, because it optimizes the adaptation of the motion when the

environment changes unexpectedly[1]. It was also suggested that the proactivity might be the cause of the illusory inversion of causality necessary to explain the concept of subjectivity owned by normal human beings[4].

## III. PURPOSE OF THE PRESENT STUDY

We studied the human control mechanism when the target in the previous studied is replaced by another human being and ask two subjects to pursue symmetrically a mutual tracking to clarify the following questions;

- 1) The position error correction mechanism and the predictive tracking mechanisms changes form one to the other with the same experimental parameters with the previous constant speed target experiment?
- 2) The power spectrum of the hand motion in position error correction region in the present experiment is different from the one in the previous constant speed target experiments?
- 3) The hand motion in the predictive tracking region in the present experiments is different from the one in the previous constant speed target experiments?
- 4) One moves proactively to the other in the predictive tracking region in the same way with the constant speed target tracking? , or do they take turn? Or one moves proactively to the other?
- 5) What is the condition for the successful real time communication?

## IV. EXPERIMENTAL METHOD

Hand-tracking experiment is a paradigm to trace a moving object to reveal a mechanism of visual motion control based on perception of position and velocity. In mutual tracking experimental system, cross feed-back system was set up via two computers connected through cross-cable. The time-delay of transmission speed was regulated less than 10 millisecond to perform reasonable accuracy for mutual tracking of human.

Six male and female subjects (20 to 33 years old) participated in the present hand-tracking experiments. A subject was seated at 50 cm in front of a computer screen and was asked to trace a moving visual target (a red closed circle of 6 mm diameter) as accurately as possible by the motion of a cursor (a blue closed circle of 6 mm diameter) in the screen produced by hand motion through a mechanical computer mouse.

The subject was asked to follow the programmed target for 10 seconds in order to keep the tracer velocity in the mutual

tracking experiments, and after 10 seconds the target was switched to the tracer of other person. The subject was asked to keep the initial velocity shown by programmed target as accurately as possible.

This mutual tracking lasts for 40 seconds, and the position of two tracers was sampled every 20 millisecond. 10 trials were recorded to calculate an average value in each experimental condition. In this study, we show the results of one pair. Other pairs showed the same trend. In the following section, three types of experimental condition are explained.

#### A. Fully visible tracking experiment

Target was shown in the entire circular orbit at the constant speed. Programmed target frequency was set to 0.1 Hz, 0.3 Hz, 0.5 Hz, and 0.7 Hz in the first 10 seconds of tracking.

#### B. Read-in tracking experiment

First, subject A and subject B performed the mutual tracking, and secondly, subject B performed tracking on the target whose time-development was read-in from the previous mutual tracking experiments.

#### C. Intermittent-blind tracking experiment

The circular orbit was constructed by two target-hidden regions (each 30 percent at the top and the bottom) and two target-visible regions (each 20 percent in horizontal location) as shown in Fig.1.

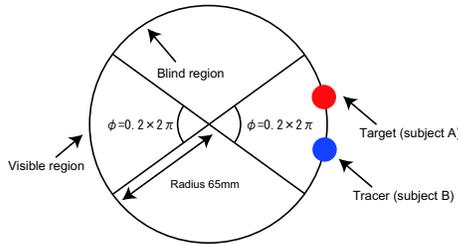


Fig. 1. Display of intermittent-blind tracking experiment : the circular orbit was constructed by two target-hidden regions (each 30 percent at the top and the bottom) and two target-visible regions (each 20 percent in horizontal location)

## V. RESULTS AND DISCUSSION

#### A. Fully visible tracking experiment

Even though, subjects try to keep the initial velocity, their tracing velocities are relaxed eventually to a velocity determined by mutual tracking (communication frequency). First, we examine the communication frequency as a function of the programmed frequency. As shown in Fig. 2, the communication frequency is always less than the programmed frequency.

Fig.3 shows the power spectrum of tracer velocity when the communication frequency is relatively low. In the previous target tracking experiments [2], Gaussian-like distribution in which the peak was located around 1 Hz was found. However, in mutual tracking experiments, there is no such a broad peak in the corrective motion for the relative phase

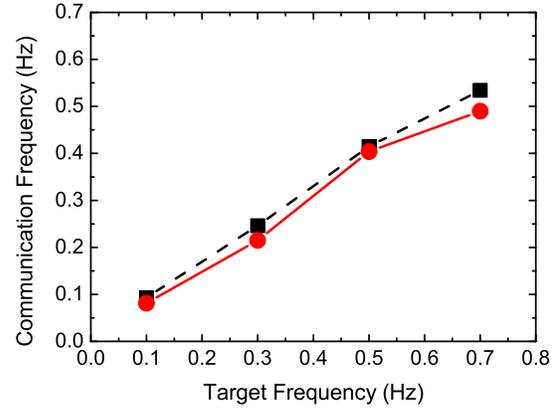


Fig. 2. Communication frequency as a function of target frequency in mutual tracking experiments: a solid line represents fully visible tracking experiments, and a dashed line represents intermittent-blind tracking experiments.

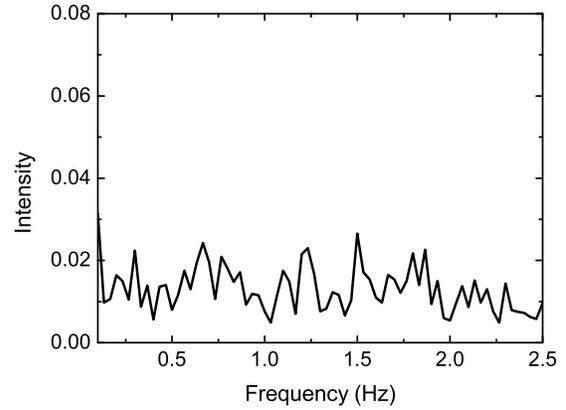


Fig. 3. Power spectrum of tracer velocity in fully visible experiments : the presented target frequency is 0.1 Hz.

difference, therefore, spectrum profile extends to higher frequency with a long tail.

Fig.4 shows a correlation function of tracer velocity of two subjects. Concave shape is found around the time-delay 0, and correlation coefficient has two peaks around the time-delay 0, which are located at the delay time of +0.3-0.4 second and -0.3-0.4 second. This time-delay indicates the time-delay of visual-motor system in the corrective movement.

There are two peaks in the correlation function, which means that the leading person is altered each other. In one time duration, the person A leads the person B, and in another time duration, the person B leads the person A. These two modes are altered in the mutual tracking experiment when the communication frequency is relatively low.

There should be only one peak if there were one mode in tracking, this fact is discussed with experimental results in the next paragraph. We suggest that this exchange of

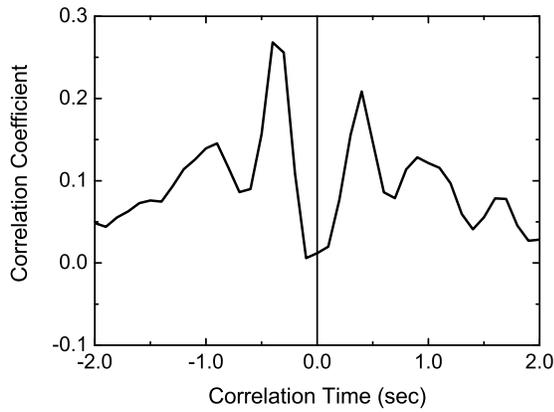


Fig. 4. Velocity correlation function in fully visible tracking experiments : the presented target frequency is 0.1 Hz.

two modes (the leading mode and the following mode) is reflection of spontaneous action. Note that this exchange of two modes has no definite time-scale, leading to the long-tailed power spectrum in tracer velocity (Fig.3).

On the other hand, the center of relative phase distribution is located at 0, indicating that corrective movement functions reasonably well.

### B. Read-in tracking experiment

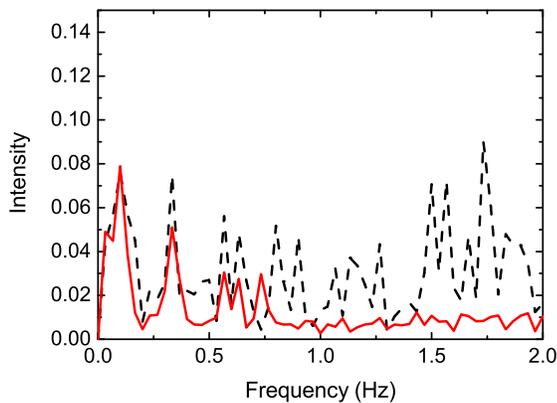


Fig. 5. Power spectrum of tracer velocity in read-in tracking experiments : the presented target frequency is 0.1 Hz. Read-in data is shown by a dashed line.

In read-in tracking experiments, a time-development of target is taken from a first mutual tracking experiment. The movement of tracer does not affect the movement of the target in this experiment.

Power spectrum of tracer velocity in read-in tracking experiment is shown in Fig.5. The curve profile at low frequency region is very similar to those of the tracking partner, the subject simply follows the time development of read-in target (though fails in the higher frequency).

Compare to the case of mutual tracking, there is only one peak in the velocity correlation function in read-in

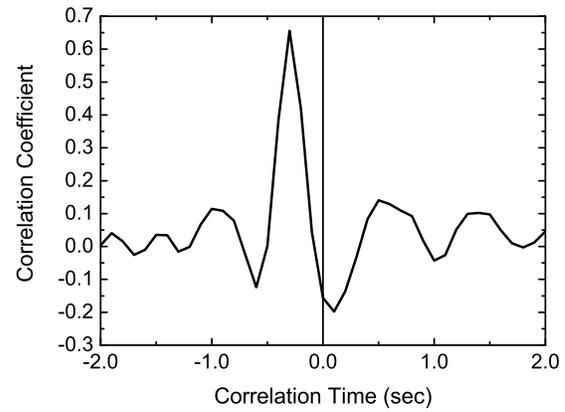


Fig. 6. Velocity correlation function in read-in tracking experiments: the presented target frequency is 0.1 Hz.

tracking experiment as shown in Fig.6. The peak at -0.3 second simply indicates the time-delay in visual-motor system, and confirms that two peaks at mutual tracking experiment (Fig.4) represents the spontaneous exchange of two modes (the leading mode and the following mode).

### C. Intermittent-blind tracking experiment

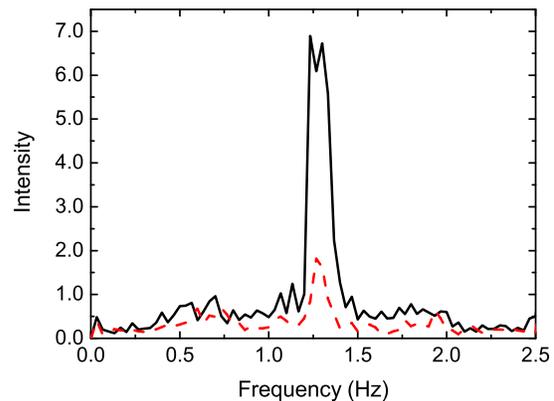


Fig. 7. Power spectrum of tracer velocity in intermittent-blind tracking experiments : the presented target frequency is 0.7 Hz. Visible region is two of 20 percent belt in horizontal location. A solid line represents the subject A, and a dashed line represents the subject B.

In intermittent-blind tracking experiments, when the preset target frequency is higher than 0.3 Hz, there appears a peak at  $2f$  (communication frequency) as shown in Fig.7. This peak indicates the rhythmic component in hand motion. The rhythmic component is strengthened at higher communication frequency. The strength of the rhythmic component between two persons is different.

In the case of intermittent-blind tracking experiments, the velocity correlation function shows no time-delay as shown in Fig.8, *i.e.*, subjects trace each other in synchronized manner with no time-delay. The creation of the rhythmic component is necessary for the synchronized motion between two persons.

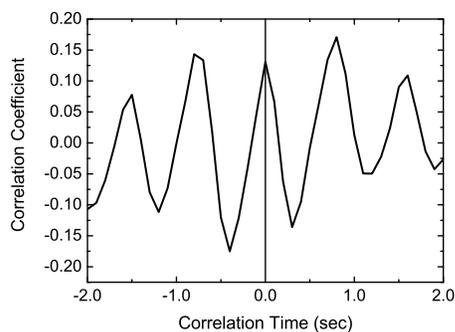


Fig. 8. Velocity correlation function in intermittent-blind tracking experiments: the presented target frequency is 0.7 Hz. Visible region is two of 20 percent belt in horizontal location.

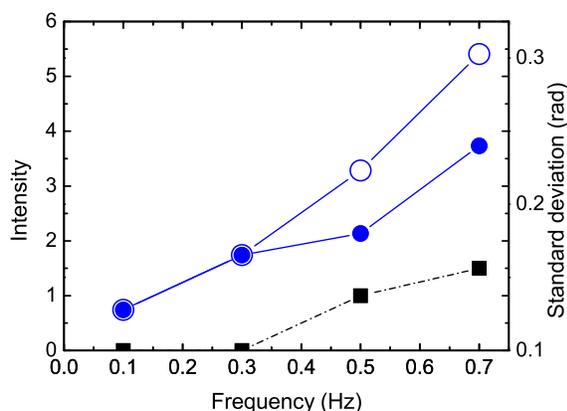


Fig. 9. Standard deviation of relative phase difference and intensity of rhythm in intermittent-blind experiments: the intensity of rhythmic component(  $\circ$  ), the standard deviation in the entire circle(  $\bullet$  ), the standard deviation without contribution from rhythmic component(  $\blacksquare$  ).

In mutual tracking at higher frequency, we find the synchronization of the rhythmic component in the hand motion. However, there could be a difference in amplitude of rhythm between two person(Fig.8). This difference contributes to the total standard deviation. Therefore, this contribution should be subtracted from the total standard deviation of the relative phase difference.

Fig.9 shows the standard deviation of the relative phase difference and the intensity of rhythmic component. One can see that the standard deviation without contribution from the rhythmic component shows a reduction of fluctuation of the relative phase difference. A common rhythm is created by which the fluctuation of the mutual positional error is reduced.

## VI. EXPERIMENTAL SUMMARY

The present study together with the previous study provided following results, when a subject is asked to track the target as accurately as possible by using visual information,

A. When the target moves autonomously independent of the tracer.

- 1) When the target moves in a complicated way, the tracer always tracks the target with delay in the power spectrum up to 1 Hz.
- 2) When the target motion is simple and predictable, the tracer moves proactively to the target.

B. When the target is another person who also is asked to track the other as accurately as possible.

- 1) When the motion is slow enough for the subjects to obtain the information of the other all the time, the period when the velocity of subject A precedes that of the subject B and the period in the reversed case appears in turn with random timing. The correlation function of the velocities of the two subjects takes maximum values at  $t = +0.3-0.4\text{sec}$  and at  $t = -0.3-0.4\text{sec}$ .
- 2) When the motion is fast, the subjects cannot obtain all the information of the other, and when possible the subjects create a common rhythm. The rhythm is used for predictive control when the information is not obtained. The error correction mechanism is used when the information of the other is obtained. By the combination of the two mechanism the correlation of the velocities of the two subjects takes a maximum value at  $t = 0$ .

## VII. CONCLUSION

In the verbal communication a person A speaks or writes and another person B listens or reads A in a interval, and in the next interval the inverse situation takes place. This may be called a communication by changing the subjectivity between them. In the present study of motional communication a similar situation was observed when the speed of the process is slow. On the other hand, when the process is fast, a common rhythm is created by which the fluctuation of the mutual positional error is reduced. This is a new type of optimization of the cooperative adaptation when the process is fast.

## VIII. ACKNOWLEDGEMENT

We thank useful discussion with Prof. Ikegami of Tokyo University and Prof. Miyake of Tokyo Institute of Technology.

## REFERENCES

- [1] Ishida, F., and Sawada, Y., Human hand moves proactively to the external stimulus; An evolutionary strategy for minimizing transient error, *Physical Review Letters*, 96, 168105 (2004).
- [2] Hayashi, Y., Tamura, Y., Sase, K., Sugawara, K., and Sawada, Y., Intermittently-visual tracking experiments reveals the roles of error-correction and predictive mechanisms in human visual motor control system, submitted to *Journal of control, measurement, and system integration*.
- [3] Hayashi, Y., Tamura, Y., Sugawara, K., and Sawada, Y., Why the hand motion proceeds the target in tracking experiment?, *Proceedings of The 3rd International Symposium on Mobiligence*.
- [4] Y. Sawada and F. Ishida, Anticipation and proaction: how can one behave subjectively?, *Journal of control, measurement, and system integration*, 48, 60-65, (2009).

# Representation of self and other in the parieto-premotor network

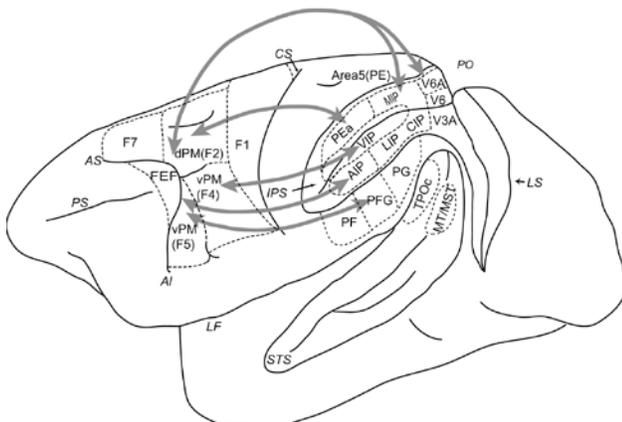
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**Abstract— It is known that parietal cortex is much concerned with visuo-tactile integration that should be related to self body representation. Furthermore, it is claimed that reafference signal from motor area to parietal cortex also may contribute sense of agency. This system may be shared with sensory motor control mechanisms in the brain. In this year, we report the results of information analysis of spike frequency of single neurons of area AIP with collaboration of University of Electro-communication. This analysis should reveal stream of information in the parieto-premotor network that would be related to distal hand control and also corporeal awareness. We Also found that some of parietal bimodal neurons were concerned with representation of both self and other's body.**

## I. Information analysis for hand manipulation related activity of AIP neurons

THE parietal cortex is much involved in self body representation. For corporeal awareness: especially sense of agency, integration of visual-somatosensory feedback and reafference signal from motor area is very important. There may be some mechanisms to compare these information in the brain. Many neurons in the parietal area AIP (Fig.1) have been known to be related to distal



parieto-premotor networks From Ref. [1]

hand manipulation control. This area has also much anatomical connection with ventral premotor cortex F5, that is also concerned to execution of distal hand movement. The parietal-premotor network has important roles for visuo-motor control.

The visual neurons of AIP showed selectivity for 3D spatial properties of objects to be manipulated. On the other hand, some neurons in superior parietal lobule showed somatosensory response for passive multi-joint movement. Furthermore, we found some bimodal neurons that responded to passive arm-joint movement and also moving visual stimuli. These evidences suggest that parietal cortex have a role of monitoring arm movement.

In our previous study[2], we compared neural activity during hand manipulation tasks in which a monkey was required to manipulate 3D objects with one hand using full vision and in the dark or just fixate on the object for manipulation without grasping it. We classified these neurons of AIP into three different types that were activated during the task: **motor dominant**, **visual dominant** and **visual-motor neurons**. **Motor dominant neurons** fired during manipulation in the full vision condition and in the dark but did not show any significant difference in level of activity in the both conditions. These neurons did not respond to the presentation of objects, or to any somatosensory stimuli, and thus were considered as being related to the motor component. **Visual dominant neurons** fired during manipulation in the full vision condition but not during manipulation in the dark. **Visual-motor neurons** were less active during manipulation in the dark than in the light. These visually responsive neurons (visual dominant or visual-motor neurons) fired during fixation on the objects, coding three-dimensional properties of the objects (**object type**), that is, each of these neurons was selective to a particular shape, orientation, or size of objects. However, the rest of the visually responsive neurons did not show any activity to the sight of objects. Because this type of neuron showed selectivity for type of grasping (**non-object type**), the activity may reflect the view of the moving hand configuration.

On the other hand, in the ventral premotor cortex F5, activity of neurons showed selectivity to the type of hand

movement, such of precision grip, finger prehension, and whole-hand grasping. Rizzolatti's group coined the term "motor vocabulary" for these different types of movements. Functional properties of neurons of this area were similar to those of AIP[3]. A group of grasping-related neurons in F5 was activated when the monkey fixated on the objects to be grasped. This category of neurons was active during grasping in the dark, like visual-motor neurons in AIP. Furthermore, the other group of grasping neurons did not show any visual properties like those of motor dominant neurons in AIP.

Although the properties of these neurons in AIP and F5 are very similar, different types of these neurons in the different areas should have different functional roles. In this study, to reveal dynamics of information processing intra-area and also inter-area of AIP-F5 network, information analysis was adopted using real spike data recorded from inferior parietal area AIP. The study has been done by collaboration with Sakaguchi's group in University of Electro-Communications and the results were prepared to be published[4].

### 1. Materials and methods

In the recording session, the monkeys were required to manipulate an object with guidance of LED spot (hand manipulation task). The monkey was asked to fixate on the object, then reach, and grasp it. The task was constructed with three different phase; fixation period in which the monkey just fixated the object, reaching period in which the monkey reached and manipulate the object, and finally holding period in which the monkey hold the object. Six different objects, plate, ring, cube, cylinder, cone and sphere were adopted for grasping. The information analysis was applied to spike data of hand manipulation neurons from AIP. Analysis for each type of neurons was done separately. The calculation was performed with a following function in each 50 ms during task trials.

$$\begin{aligned}
 I(R;S) &= H(R) - H(R|S) \\
 &= -\sum_r p(r) \log p(r) + \sum_s p(s) \left[ \sum_r p(r|s) \log p(r|s) \right] \\
 &= \sum_{s,r} p(s,r) \log \frac{p(s,r)}{p(s)p(r)} \\
 MI(k) &= -\sum_r p_k(r) \log p_k(r) \\
 &+ p(S_k) \left\{ \sum_r p(r|S_k) \log p(r|S_k) \right\} + p(S_k^*) \left\{ \sum_r p(r|S_k^*) \log p(r|S_k^*) \right\} \\
 &= -\sum_r p_k(r) \log p_k(r) + \frac{1}{2} \left\{ \sum_r p(r|S_k) \log p(r|S_k) + \sum_r p(r|S_k^*) \log p(r|S_k^*) \right\}
 \end{aligned}$$

In this function, H indicates entropy. S and R are sets of the objects and number of spikes, respectively. The conditional entropy  $H(S|R)$  is the uncertainty about S after observing spikes. In this study, MI was calculated in all possible combination of two objects among six. Then

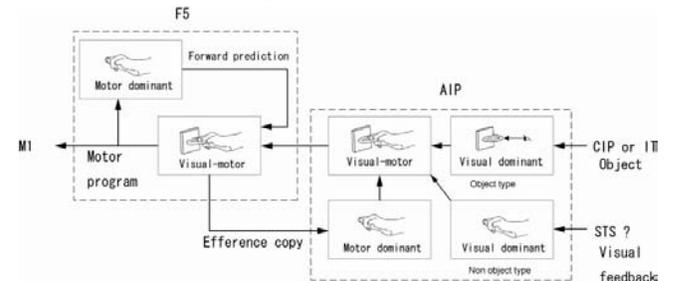
relationship between the timing of peak and the task phase was examined in each type of neurons.

### 2. Results

It was revealed that MI showed much difference among type of neurons. Visual dominant and Visual-motor neurons object type neurons showed MI peak value in the fixation period and it sustained during whole task period. This phenomenon was also similar both in the independent neuron and in the mean MI of the population. MI was very high with some particular content (the combination of two objects) that had different 3D futures. This supports our idea that activity during fixation period reflected 3D information of the objects to be grasped. Furthermore, among different contents, we found several hundred ms of difference in the latency after the onset of the object presentation even if we calculated MI in the same type of neurons or also individual neuron. This may suggest that processing of each object features occur separately at the different timing. Some visual-motor neurons showed change of content when the task was ongoing from fixation period to reaching and holding period. This suggest that this type of neurons encode not only visual object information, but also some other information. We expected the information were also related to visual feedback or copy of motor plan received from the ventral premotor area.

On the other hand, MI of motor dominant neurons, and visual-motor or visual dominant non-object type neurons started to increase in the reach and hold periods. The latency of motor dominant neurons was a bit earlier (a few ms) than non-object type neurons. This suggests that these motor dominant neurons and non object type neurons has functionally different information, although in our previous experiment, both motor dominant neurons and non object type neurons were selective for shape of the hand to grasp. In these types of neurons, contents of MI remained constant until the end of the task.

These results support our previous speculation about functional model of AIP and F5 neurons. We can explain stream of information as follows. Object type neurons analyze 3D spatial properties of the object and may contribute to affordance selection. This information is held in the visual dominant neurons, while visual-motor neurons send this visual information to premotor cortex. Premotor cortex may select appropriate motor plan



according to this visual information.

Motor dominant neurons is considered to be the copy of motor plan; namely efference copy. On the other hand, non-object type visual dominant neurons represent visual feedback. Visual-motor non-object type neurons have a role to mach visual feedback and efference copy.

## II. Representation of spatial reference frame in AIP

As we described, neurons in area AIP represent 3D object features to be manipulated. In the case of reaching control, the target position is encoded in body-centered frame. However, in grasping control, it is not much clear which frame of reference is used for encoding target position in the object. For example, if there are multiple affordances in the object, the relative position of the affordance in the object is necessary to select one of these affordances.

In the pilot study, we trained the monkey to manipulate a push button on the one of surface of square box, and recorded neurons in area AIP. In the experiment, a push button was fixed in the same position on the body-centered frame, while we changed the target position relative to the object.

We found some of object type neurons that encoded relative position in the object centered coordinate during hand manipulation. These neurons showed modulation in activation when the target was in the different position in the object, even though the target was in the same position in the body centered coordinate. The neurons showed consistent responses to the same relative position of the target while the monkey fixated and manipulated the object in the different position in the body-centered coordinate. Since the position of the object on the retina was always same in this condition, it was possible that the neuron encoded the position of the object in the retinal coordinates. To exclude this possibility, we tested these neurons while the fixation point was in the fixed position in the body centered frame, then we changed the position of the object relative to the fixation point. Again, we found the position invariance of the selectivity for the relative position in the object. The neurons were actually concerned to encoding target position in the object-centered coordinate.

Additionally, some of motor dominant neurons also showed selectivity for object centered position. This kind of neurons might be related to hand trajectory in the object centered frame.

## III. Corporeal awareness and AIP-F5 network

Sense of agency is one of the important components of awareness of self body. For the sense of agency, it is considered that a mechanism to compare sensory feedback and efference copy is necessary for sense of agency. In our study, possible signal related to efference copy was found

in area AIP by information analysis. This suggests that the comparator exist in the parietal cortex. Actually, in this project of Mobiligence we found some neurons that represented visual feedback during hand manipulation task. These neurons also showed properties of mirror neurons[1].

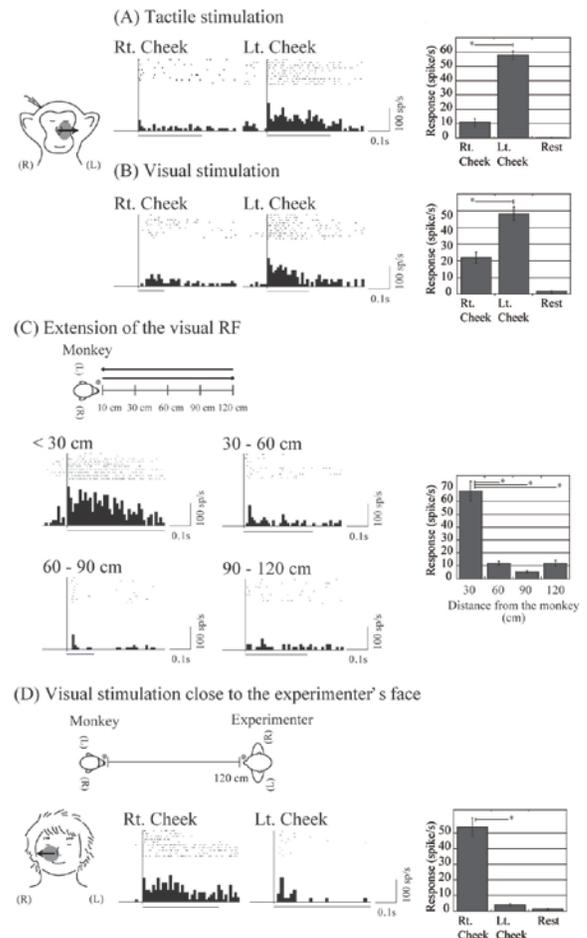
## IV. Representation of other's body in the brain

The target to be manipulated is represented on the object centered frame of reference. On the other hand, we also revealed that other's body representation was shared with one's own body mapping[5].

Recent neurophysiological studies suggest that self and other are represented on the same neuron. Mirror neurons encode visual action of other on the neurons that is related to motor execution of one's own action.. These neurons suggest that other's body is mapped in the brain, not only self body. We expected that a map of self body parts is referred for recognition of other's body. We found some group of neurons in the parietal cortex and the results support our hypothesis. These results were reported on the J. Cognitive Neuroscience in this year.

In the experiment, after mapping of the tactile and visual RFs, an experimenter confronted with the monkey.

### Mirror image



To ensure that bimodal neurons also responded to stimuli within other's peripersonal space, visual stimuli were presented in the vicinity of the experimenter's body parts and explored visual RFs.

We recorded bimodal neurons from VIP and 7b (PF/PFG). Almost 10% bimodal neurons also responded to the visual stimuli presented near the experimenter's body parts. Remarkably, visual RFs around the experimenter's body parts corresponded with location of bimodal RFs on the monkey's body parts. As shown in figure, the neuron showed tactile RFs particularly on the left cheek of the monkey and visual RFs extended within 30 cm from the cheek. Furthermore, when the monkey observed visual stimuli moving close to experimenter's left cheek, the neuron particularly discharged. This neuron showed strong directional selectivity, that is, preferred to rightward movement with respect to the monkey's perspective. Importantly, the visual RF around the experimenter's face was in a mirror image position with respect to the monkey's visual RF. Furthermore, to elucidate reliability of visual RFs on the experimenter's body, we investigated activity of these neurons when the experimenter shifted the sitting position to the left or right side of the monkey. The RFs remained on the same body part and were within peripersonal space (<30cm) of both the monkey and experimenter.

These results suggest that other's body parts are encoded in the same area that is related to one's own body parts, and a map of self body parts is referred for recognition of other's body. For the adaptive behavior in the robotics, it is a big issue how the system recognizes other's body. In the imitation, the system should superimpose other's body onto one's own. Our data will provide important ideas for matching systems between one's own body and other's.

The response properties of these neurons may appear to be associated with those of mirror neurons. These mirror neurons have been proposed to play important roles in action recognition and imitation learning. For these cognitive functions, representation of other's body is necessary in one's own brain. It is noteworthy that VIP has much connection with PF/PFG in which mirror neurons were recorded. It is possible that VIP send other's body representations to the mirror neuron.

The object and other's body are both in the environment, but it seems to be represented by different ways in the brain. We need to study the relationship between the reference frames of the body and object in the future.

#### ACKNOWLEDGMENT

The MI analysis mainly has been done by Mr. Takashi Shimizu and Dr. Fumihiko Ishida with leadership of Prof. Yutaka Sakaguchi in University of Electro-Communications. We gratefully acknowledge the collaboration.

#### REFERENCES

- [1] Murata, A. and H. Ishida, Representation of bodily self in the multimodal parieto-premotor network, in *Representation and Brain*, S. Funahashi, ed, Springer. p. 151-176. 2007
- [2] Murata, A., V. Gallese, G. Luppino, M. Kaseda, and H. Sakata, Selectivity for the shape, size, and orientation of objects for grasping in neurons of monkey parietal area AIP. *J Neurophysiol.* **83**(5): p. 2580-601. 2000
- [3] Murata, A., L. Fadiga, L. Fogassi, V. Gallese, V. Raos, and G. Rizzolatti, Object representation in the ventral premotor cortex (area F5) of the monkey. *J Neurophysiol.* **78**(4): p. 2226-30. 1997
- [4] Sakaguchi, Y., F. Ishida, T. Shimizu, and A. Murata, Time course of information reresetation of macaque AIP neurons in hand manipulation task revealed by information analysis. (submitted)
- [5] Ishida, H., K. Nakajima, M. Inase, and A. Murata, Shared Mapping of Own and Others' Bodies in Visuotactile Bimodal Area of Monkey Parietal Cortex. *J Cogn Neurosci.* **22**(1): p. 83-96. 2009

# Induction and estimation of sensorimotor patterns between self and others based on Mirror Neuron model

Tetsunari INAMURA and Keisuke OKUNO

**Abstract**—We propose an adaptive acquisition method to infer model of others’ sensorimotor patterns, using mimesis model, which is our previous work. The model abstracts others’ motion patterns and links to a primitive symbol representation based on self body configuration. It, however, doesn’t concern the structural difference between self and other. Furthermore, unobservable inner sensory information such as torque cannot be treated. We utilize symbol communication to solve these problems. Through experiments on virtual environments, we have confirmed the feasibility of our proposed method.

## I. INTRODUCTION

Inamura *et al* have proposed *proto-symbol space* based on *mimesis theory* as an abstract representation of sensorimotor patterns for humanoid robots.[1][2]. The proto-symbol space describes relationship between abstracted representation of sensorimotor patterns based on Hidden Markov Models. The space is constructed by distance information between the abstracted representations using Kullback-Leibler divergence and multi-dimensional scaling method. In this proto-symbol space, motion patterns are able to be transformed into static state points, that is proto-symbols, even though an input motion pattern is unknown.

We extended the method in order to apply the concept ‘behavior imitation’ to adaptive behavior generation according to any changes of situation, in the four-year research project on *mobiligence*. In the two-year project of the first half, we proposed a method to integrate not only motion patterns but also sensor patterns to be abstracted by the *proto-symbol space*. Additionally, interpolation and extrapolation of motion patterns are realized with creating internal/external dividing points between two positions of the proto-symbols[3]. Motion imitation, that is combination of recognition and generation of motion patterns, has been realized with integrating these two calculation, even though the original motion patterns are unknown and novel.

In the previous works, motion imitation was discussed between human beings and humanoid robots, however, a problem has been remained that abstract representation of others’ sensorimotor patterns was not considered. There was an assumption that the same physical condition was shared by learner and performer even if the one was human being and the other was humanoid robot. To clear the problem, a mimesis model that can estimate other’s sensor pattern should be realized, by establishment of connection between

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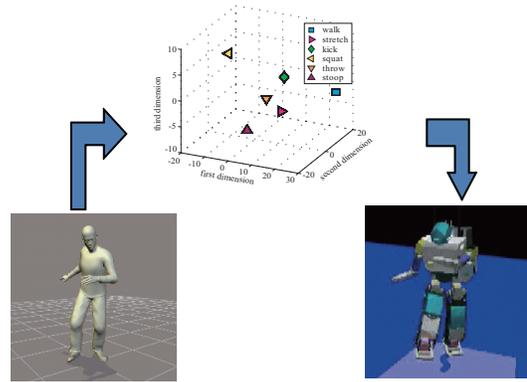


Fig. 1. Conventional mimesis model that uses sole proto-symbol space

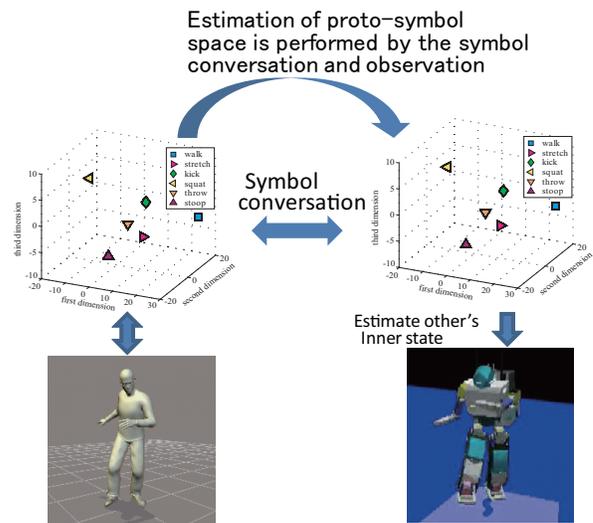


Fig. 2. Proposed mimesis model that consists of two proto-symbol spaces

other’s proto-symbol space and self proto-symbol space as shown in Fig.2.

In this paper, we propose an extended model of our previous method to estimate other’s sensor patterns with consideration of difference of physical conditions between self and other. Especially, we focus on gradual acquisition strategy to estimate unobservable other’s sensor pattern with making communication between self and other.

Fig.1 shows a process flow of the conventional imitation. Fig.2 shows a flow of the proposed method by two proto-symbol spaces of self and other.

## II. ACQUISITION OF ESTIMATION MODEL OF OTHER'S SENSORIMOTOR PATTERNS

As shown in Fig.2, two different proto-symbol spaces should be used for other and self to realize imitation with consideration of sensor patterns. However, a problem should be solved that other's motion patterns cannot input to self proto-symbol space where we realize motion imitation with a style shown in Fig.2. Additionally, since other's sensor pattern is unobservable, a certain estimation function from observable motion pattern to the sensor pattern is also required. We therefore consider a strategy in which the *self* has estimation model of the other's proto-symbol space as well as the self proto-symbol space.

To simplify the explanation, we use  $PSS_{self}$  as a self proto-symbol space,  $PSS_{other}$  as a proto-symbol space of other's,  $\hat{PSS}_{other}$  as an estimation model of other's proto-symbol space owned by self. Since other's sensor patterns are unobservable, a sensorimotor pattern database  $D_{other}$  which is used to construct  $\hat{PSS}_{other}$  should be set by a copy of  $D_{self}$  which is used to construct the  $PSS_{self}$ . In the acquisition phase, the following procedures are repeated.

- 1) Consider an objective motion pattern that can be shared between self and other. Estimate an expected sensor pattern that should be felt by other using  $\hat{PSS}_{other}$ .
- 2) Detect a difference between estimated sensor pattern and actual sensor pattern with conversation between self and other.
- 3) Modify the estimated sensor pattern based on the result of dialogue, then input the modified sensor pattern into database  $D_{other}$  to be used for the construction of  $\hat{PSS}_{other}$ .

Estimated other's proto-symbol space  $\hat{PSS}_{other}$  will be getting closer to the proper proto-symbol space  $PSS_{other}$  with repetition of above procedures.

## III. ACQUISITION OF PROTO-SYMBOL SPACE BASED ON DIALOGUE

### A. Basic strategy of the acquisition

In the concrete, consider an experiment in which a humanoid robot  $R_1$  try to estimate sensorimotor pattern of another robot  $R_2$  whose physical condition is different from  $R_1$ . Let a sequence of joint angle vector be an example of objective motion pattern that can be shared between self and motion, a torque pattern be an unobservable sensor pattern.  $D$  a database of sensorimotor pattern consists of  $m$  motion patterns  $M = (M_1, M_2, \dots, M_m)$  as sequence of joint angle vector and  $m$  sensor sensor patterns  $S = (S_1, S_2, \dots, S_m)$  as torque vector for each joint. The problem could be regarded as an acquisition of a proto-symbol space  $\hat{PSS}_{R_2}$  based on the database  $D$ .

Here, the following procedure is used for the acquisition of  $\hat{PSS}_{R_2}$

- 1) Consider a database  $D_{R_2}$  that is used by  $R_1$  to estimate  $R_2$ 's proto-symbol space  $\hat{PSS}_{R_2}$ . Let the initial state of  $D_{R_2}$  be copy of  $D_{R_1}$  that is set of  $M$

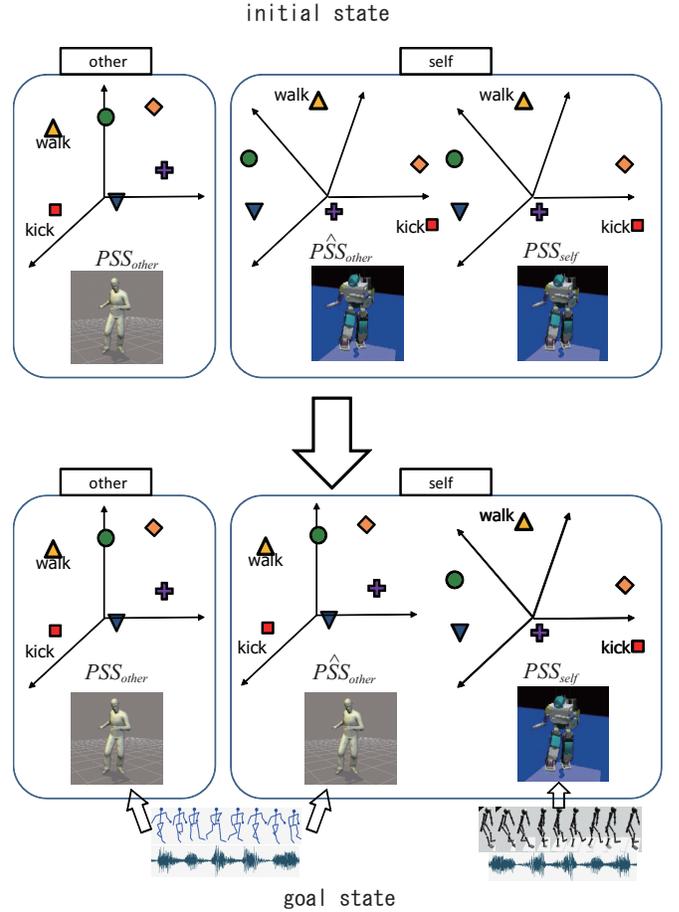


Fig. 3. Concept of the acquisition of other's proto-symbol space

and  $S$  of  $R_1$ . In other words, the initial state of  $\hat{PSS}_{R_2}$  is  $PSS_{R_1}$ .

- 2) Input a motion pattern  $M_i$ , which is stored in the database  $D_{R_2}$ , into  $\hat{PSS}_{R_2}$  to calculate a sensor pattern  $\hat{S}_i$ . This procedure corresponds to estimation of  $R_2$ 's sensorimotor pattern by  $R_1$
- 3)  $R_2$  performs the motion pattern  $M_i$  by its own body, then transfers the felt sensor pattern  $S$  into a symbol index  $k_{R_2}$ .
- 4)  $R_1$  also transfers the estimated sensor pattern  $\hat{S}_i$  into a symbol index  $k_{R_1}$  to detect difference between estimated sensor pattern  $\hat{S}_i$  and actual sensor pattern  $S$ . After that,  $R_1$  starts a dialogue to confirm whether the two symbol indexes are the same or not.
- 5) Modify the estimated sensor pattern  $\hat{S}$  according to the difference between  $k_{R_1}$  and  $k_{R_2}$ . A corresponding pattern in the database  $D_{R_2}$  will be replaced with the modified  $\hat{S}$ .  $\hat{PSS}_{R_2}$  is re-constructed by the modified database.
- 6) Repeat the above procedures to acquire  $\hat{PSS}_{R_2}$ .

An outline of the above process is depicted in Fig.4.

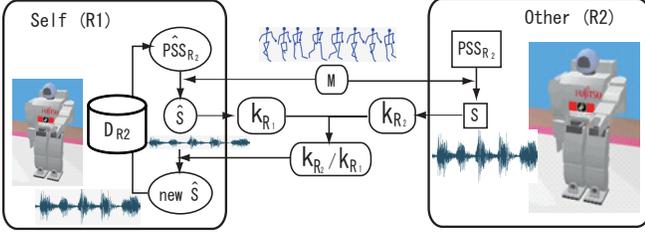


Fig. 4. Block diagram of the revision of estimated proto-symbol space

## B. Experiment and Evaluation

In the experiment, two virtual humanoid robots  $R_1$  and  $R_2$  are used in a simulator environment. Structure of both of the robots is same as HOAP-2 produced by Fujitsu Corp; however weight of  $R_1$  is 2.4[kg] and the one of  $R_2$  is 4.8[kg]. An experiment is performed with torque pattern on the right hand for four basic motion patterns.

First of all, a proto-symbol space  $PSS_{R_i} (i = 1, 2)$  is created by the four basic motion patterns and measured sensor pattern by  $R_1$  and  $R_2$ , where let torque value for the right elbow, pitch and roll rotation torque on the right shoulder  $[\tau_1 \tau_2 \tau_3]$  is set as  $S$ . Joint angle for the same joint rotation  $[\theta_1 \theta_2 \theta_3]$  is set as  $M$ .  $\theta_i$  and  $\tau_i$  are time-series data.

Symbol indexes  $k$  used in the dialogue is calculated by the following procedure.

- Let  $\tau_{MAX}$  as the maximum torque value measured by  $R_2$ . Consider a normalized torque value defined by

$$g = \frac{1}{T} \int_0^T \frac{|\tau_1(t)| + |\tau_2(t)| + |\tau_3(t)|}{\tau_{MAX}} dt \quad (1)$$

is calculated, where  $T$  is time length of the  $\tau_i(t)$ ,  $\tau_{MAX}$  is constant value as 0.4[Nm].

- Dividing an interval of the  $g$  into  $d$  segments equally. Several symbol indexes  $k$  are assigned following to the Table.1.

TABLE I

RELATION BETWEEN EXPRESSION AND DENSITY OF THE EXPRESSION

k	d=2	d=4	d=6	d=8
1	light	light	very light	quite light
2	heavy	bit light	light	very light
3	-	bit heavy	bit light	light
4	-	heavy	bit heavy	bit light
5	-	-	heavy	bit heavy
6	-	-	very heavy	heavy
7	-	-	-	very heavy
8	-	-	-	quite heavy

When the sensor pattern  $S_i$  in the database should be modified following to the result of dialogue, amplitude of  $S_i$  is amplified by  $k_{R_2}/k_{R_1}$ , that is ratio between  $k_{R_1}$  and  $k_{R_2}$ . Perform the modification against four basic motion patterns. If at least one sensor pattern were modified, the proto-symbol space would be revised by the modified database.

To evaluate the performance of the estimation of proto-symbol  $PSS_{R_2}$ , the following evaluation criteria are considered against  $N$  unknown motion patterns  $M'_i (i = 1, \dots, N)$

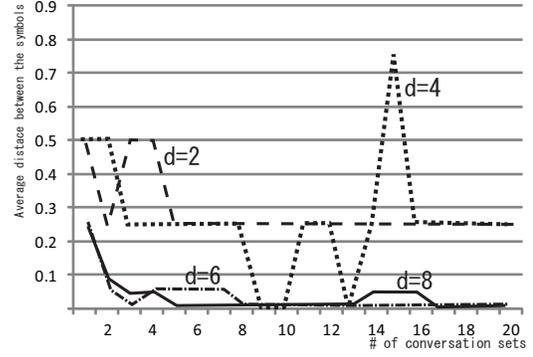


Fig. 5. Difference of the symbol index for basic motion patterns

- Concordance ratio of the symbol indexes*: Ratio that the symbol indexes  $k_{i_{R_1}}$  and  $k_{i_{R_2}}$  are concordant among  $M'_i$ .
- Difference between symbol indexes*: This criteria indicates degree of unlikeness between each symbol indexes defined by:

$$k_{diff} = \frac{1}{N} \sum_i \frac{|k_{i_{R_1}} - k_{i_{R_2}}|}{d} \quad (2)$$

Here, the interval of  $k_{diff}$  is  $0 \leq k_{diff} \leq 1$  from the above definition.

- Estimated torque error*: This criteria is difference between estimated torque by  $R_1$  and actual torque observed by  $R_2$  using

$$e = \frac{1}{N} \sum_i |\hat{g}_i - g_i|, \quad (3)$$

where  $\hat{g}_i$  is normalized torque value of estimated torque by  $R_1$  with Eq.(1) against motion pattern  $M_i$ ,  $g_i$  is normalized torque value actually observed by  $R_2$ .

## C. Experimental results

Fig.5 indicate the criteria of difference between symbol indexes defined by Eq.(2) with the repetition of dialogue for 10 unknown motion patterns. Horizontal axis indicates the number of loop described in section III-A. (We call the number of loop as the number of dialogue.) We have performed in 4 kinds of situation where the number of expressions are different ( $d = (2, 4, 6, 8)$ ) When  $d = 4$ , the band of fluctuation was little wide. But in case of  $d = 6, 8$ , differences were suppressed. The result shows that the difference of the symbol indexes are little when many expressions were used, that is density of the expression was fine.

Next, we confirmed the criteria of estimated torque error with repetition of dialogue. Fig.6 shows progression of estimated torque  $e$  calculated by Eq.(3). In the graph,  $d = 6$  is used. torque values for both of motion pattern  $M$  in database  $D_{R_2}$  and unknown motion pattern  $M'$  for test evaluation were depicted. Error between estimated torque value and true torque value was about 0.05[Nm] at most. Estimated torque value from  $M'$  were about from 0.2 to 0.25[Nm]. Therefore,

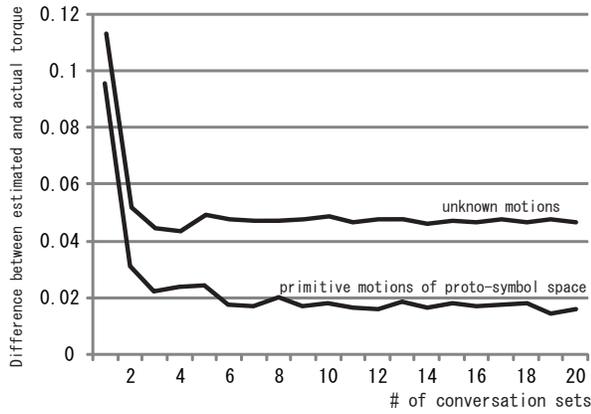


Fig. 6. Difference between estimated torque and actual torque by 6 words (d=6)

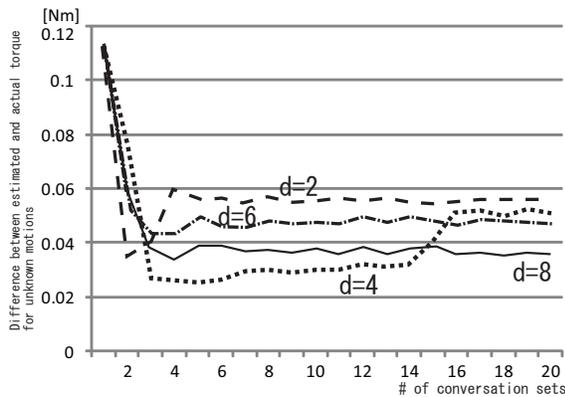


Fig. 7. Error of estimated torque for unknown motions

the error was suppressed within about 10% for known motion pattern in database  $D_{R_2}$ . Even if the target motion patterns were unknown, the error was suppressed within 20% ~ 25%.

Fig.7 shows a superposition of Fig.6 for four case of  $d = 2, 4, 6, 8$ . Since the estimated torque error was within about 20%, the capability of stable torque estimation was shown. The result have close relationship between the result by Fig.5. The one result backs up the another result[4].

#### IV. ESTIMATION OF SYMBOLIZATION STRATEGY OF SENSOR PATTERNS

However, there was a remaining problem, a symbolization strategy how to convert sensory patterns into the symbol index was given for sake of simplicity. Intrinsically, the strategy is supposed to be unknown and it should change dynamically according to situation and environments. Thus, it is required to estimate the unobservable symbolization strategy of the other. It is possible to estimate the strategy by the method in the previous work[4] if sets of motions and questions are prepared properly. However, it would require as same or more number of questions as of the strategy candidates. It is because the communication method used was an open question and there are almost infinite number of choices for the answers. When interaction between robots

and humans are considered, it is better to limit the number of questions from the robot to the human and to reduce the possible choice of the answers. In other words, using closed question suits well for human robot interaction.

Thus, in a paper[5], we proposed a method, comparative evaluation question with motions, in order to have less amount of questions. In this method, the other was asked to perform two kinds of motions and answer which motion was heavier, or observed larger torque on joints. Expressing the comparison of the torque as an answer makes the method closed question. The comparative evaluation questions with motions is used in the framework of the previous work[4] in order to estimate the intrinsically unknown symbolization strategy how to convert sensory patterns into the symbol-index.

#### V. CONCLUSION AND DISCUSSION

In this research, we focus on the remained problem of our previous works, that is proto-symbol space that can be abstract sensorimotor patterns between both of self and other even though the two subjects have different physical conditions. The approach is estimation of other's proto-symbol space through repetition of dialogue. Specifically, design a dialogue protocol based on symbol index to express the inner sensor patters, and approximation method with modification of sensorimotor patterns based on dialogue, are proposed. We have also performed quantitative experiments to evaluate the proposed method and performance of the estimation of other's proto-symbol space.

Another problem is that the symbol indexes are not concerned with proto-symbols defined by the phase space structure. As a ultimate goal, symbolization should be performed with unified rule. We are planning to update our method to fit the concept of proto-symbol space not only the abstract of sensorimotor patterns, but also design of dialogue between human beings and robots.

#### REFERENCES

- [1] Tetsunari Inamura, Yoshihiko Nakamura, Iwaki Toshima, and Hiroaki Tanie. Embodied symbol emergence based on mimesis theory. *International Journal of Robotics Research*, Vol. 23, No. 4, pp. 363–378, 2004.
- [2] Tetsunari Inamura, Hiroaki Tanie, and Yoshihiko Nakamura. From stochastic motion generation and recognition to geometric symbol development and manipulation. In *International Conference on Humanoid Robots*, 2003. (CD-ROM).
- [3] Tetsunari Inamura and Tomohiro Shibata. Geometric proto-symbol manipulation towards language-based motion pattern synthesis and recognition. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 334–339, 2008.
- [4] Tetsunari Inamura and Keisuke Okuno. Estimation of other's sensory patterns based on dialogue and shared motion experiences. In *IEEE/RAS International Conference on Humanoid Robots*, pp. 617–623, 2009.
- [5] Keisuke Okuno and Tetsunari Inamura. Estimation of other's sensor patterns based on motion imitation and communication –identification of symbolization strategy for sensor by comparative evaluation questions–. In *In Proc. of International Symposium on Artificial Life and Robotics*, pp. 893–897, 2010.

# Synthetic brain modeling studies for understanding the higher order cognitive mechanisms in organizing complex actions

Hiroaki Arie and Jun Tani

## I. INTRODUCTION

The main objective of our research has been to understand the mechanisms of higher-order cognitive brain functions with particular focus on the problems of compositionality. Compositionality means that the whole can be derived by combining reusable parts; for example, complex goal-directed actions can be generated by combining reusable behavior primitives into specific sequences according to Arbib's motor schemata theory. Although it is considered in conventional cognitive science that compositionality can be achieved by means of symbol representation and manipulation of the representations at a higher cognitive level, our motivation has been to investigate an alternative process whereby compositionality could be developed in the neural dynamics of distributed activity through accumulative learning of sensory-motor experiences.

With this motivation, we have conducted a series of neural modeling studies at the connectionist level, inspired by related evidence obtained from cognitive neuroscience studies. The models have been examined in robotics experiments for the purpose of exploring novel phenomena appearing in the interaction between neuro-dynamics and physical actions which could provide us new insights to understanding nontrivial brain mechanisms.

We first studied how a set of sensory-motor patterns can be learned as behavior primitives with distributed representation by proposing a model recurrent neural network with parametric biases (RNNPB). Our robotics experiments clarified its capability for generalization in learning and also showed how learned behavior primitives can be adaptively shifted in accordance with dynamic environmental changes by means of "regression" of the current sensory inputs.

As a next step, we investigated how a set of acquired behavior primitives can be manipulated in a goal-directed manner with utilizing hierarchy. Our robotics experiments showed that a functional hierarchy can be self-organized by utilizing multiple timescale dynamics in a proposed network model such that the fast dynamics part acquires primitive patterns and the slow dynamics part learns a sequential combination of them for each action goal. Its developmental processes were detailed.

Moreover, we studied possible mechanisms of the further higher level cognitive functions assumed for the prefrontal cortex (PFC), which include the formation of abstract concepts and executive control of acquired rules. Our simula-

tion experiment suggested that mechanisms of the executive control for rule switching and self-monitoring of confidence can be developed by self-organizing the necessary functional hierarchy presumed between the PFC and the posterior cortices. The next section describes details of the research achievements which elucidate that the higher cognitive mechanisms which are developed in the dynamics of distributed neural activities can afford generalization and fluidity as well as compositionality.

## II. RESEARCH ACHIEVEMENTS

### A. Learning behavior primitives

First, we focused on the problem of how a set of behavior primitives which frequently appear in relation to a particular sensory-motor sequence pattern can be learned for generation as well as recognition. On this purpose, we proposed a dynamic neural network model(RNNPB:recurrent neural network with parametric biases)[14], [15], [16]. RNNPB is a discrete time RNN associated with PB units in which a set of sensory-motor sequence patterns can be learned in a distributed way with self-determining a specific PB vector value for each of them. The learning is conducted by means of back-propagation through time (BPTT) algorithm in order to determine the optimal synaptic weight matrix as well as a specific PB value corresponding to each of learned patterns. The learned sensory-motor sequence patterns can be regenerated by setting corresponding PB values (Fig.1a). Also, given sensory sequence patterns can be recognized by means of the PB regression scheme; the optimal PB value for reconstructing the target pattern is searched by back-propagating the error generated between the target sequence and the reconstructed one to the PB for its update (Fig.1b). Our experiment[1] showed that a set of discrete movements and periodic movements can be learned simultaneously as fixed point attractors and limit cycling ones, respectively. PB can be regarded as a bifurcation parameter shifting attractor structure from one to another. It was also found that similar patterns are learned with similar PB values. This characteristics can provide generalization capability to the system. Tani[2] showed that principal feature dimensions can be extracted in PB vector dimensions. These results suggest that the system has some generalization capability in learning. By utilizing the PB regression mechanism in an on-line way, robots can adapt to dynamically changing situations while adequately altering their own behavior patterns. As an example, a humanoid robot with 8 DOF arms was tutored to imitate multiple movement patterns demonstrated by a human experimenter[2], [12]. More specifically, the

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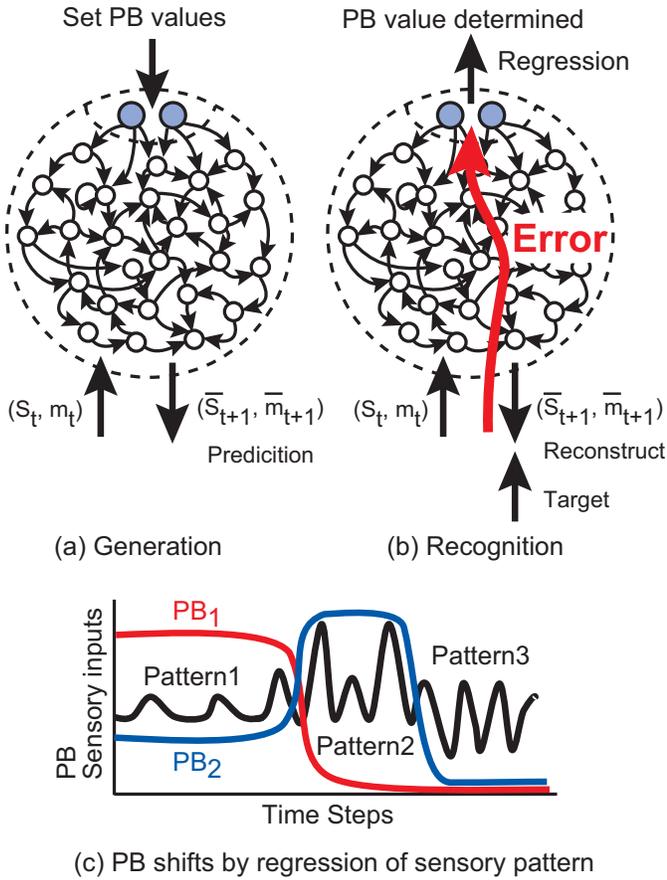


Fig1. RNNPB

robot, facing with the experimenter, learned to predict the experimenter’s movement patterns for both hands perceived through vision and also to generate its own corresponding arm movement patterns in terms of motor sequences. In the imitation game after the learning, the robot could successfully follow sudden shifts in patterns from currently engaged ones to others, as demonstrated by the experimenter, by adequately shifting the PB values (Fig.1c)[16]. In this model, the function role of PB corresponds to that of mirror neurons found in the ventral premotor cortex of monkeys by Rizzolatti’s group because the same PB activation accounts for both recognizing others’ particular movement patterns and generating own corresponding movement patterns.

As another illustrative example, the robot was tutored for two different ball-play patterns, one for laterally rolling a ball and the other for moving the ball up and down with visual perception of the ball position[3]. The ball-play patterns can switch from one pattern to another intermittently, triggered by irregular ball movements. The prediction error generated by these irregular situational changes causes modulation of the PB values by the regression, which results in the autonomous shifting of the currently engaged play patterns from one to another.

## B. Self-organization of functional hierarchy

We next investigated how a set of acquired behavior primitives can be combined in sequences to achieve various goal-directed actions. For this purpose, we proposed a continuous time RNN model, the so-called multiple timescale RNN (MTRNN)[4], which consists of a fast dynamics part with a smaller time constant in the lower level and a slow dynamics part with a larger in the higher level (Fig.2a), where the activation dynamics of each neural unit can be described as:

$$\tau \dot{u}_i = -u_i + \sum w_{ij} a_j + I_i, a_i = \text{Sigmoid}(u_i) \quad (1)$$

where  $u_i$  is the potential.

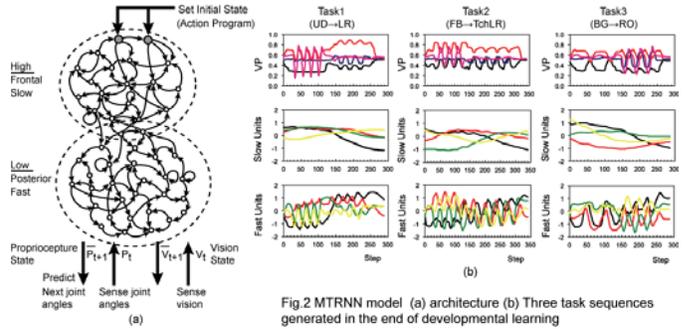


Fig.2 MTRNN model (a) architecture (b) Three task sequences generated in the end of developmental learning

We consider that the slow dynamics part may correspond to the PFC and the premotor as it is often observed that the preparatory period required to build up neural activation in these areas can take a relatively long time, of the order of seconds. The fast dynamics part, on the other hand, may correspond to the posterior cortices, especially the inferior parietal cortex (IPL). Usually, the build-up in the posterior cortical neurons is much faster, within much less than a second. The lower level network receives current visuo-proprioceptive (VP) state ( $V_t, P_t$ ) as inputs and generates its prediction outputs ( $V_{t+1}, P_{t+1}$ ) for the next time step. Here, proprioceptive state essentially means the current body posture in terms of joint angle positions for robots. The network can generate a variety of VP sequences depending on the initial states set in the higher level network by utilizing initial sensitivity characteristics. The network is trained to regenerate a set of VP sequences by determining optimal synaptic weights of the whole network and specific initial states of some of the higher level units corresponding to each of the sequences. The initial states of other neural units are set as neutral. Also, the network can generate motor imagery of the learned sequences without receiving real sensation but by feeding its own prediction to the next sensory inputs by closing the loop. A particular assumption in this model is that the IPL might generate prediction for coming multimodal sensations by receiving the top-down intention for a particular action program from the frontal cortices[5].

The MTRNN was tested in an experiment involving developmental tutoring of multiple tasks that dealt with object manipulation by a humanoid robot. Three different task sequences were considered, each of which was composed of

sequences of various behavior primitives including reaching for the object, lifting it up and down (UD), moving it to the left and right (LR), moving it forward and backward (FB), and rotating it (RO)[5]. Fig.2b shows successful regenerations of the three tasks achieved at the end of the iterative tutoring where the VP sequence and activation dynamics of the slow units and the fast units are plotted for each task sequence. It is observed that the slow dynamics generates different profiles started from each distinct initial state which result in different sequential combinations of the primitives. Therefore, it is considered that the initial state may represent an abstract action program. Also, note that the fast dynamics correlates closely with the VP sequences. These observations as well as other analytical results[4] confirmed that a set of behavior primitives are acquired embedded in the fast dynamics and that the slow dynamics in the higher level interacts differently with the fast dynamics in the lower level depending on its initial state, which results in the generation of various sequential combinations of the primitives. The role of slow dynamics might be analogous to the shifting of the PB in RNNPB. Our analysis[4] confirmed that the difference in the time constants between the two parts is essential for the self-organization of this type of functional hierarchy. This self-organization mechanism might be general, and regardless of particular learning schemes such as BPTT, because we showed that adaptation by genetic algorithm can also develop similar functional hierarchy by utilizing timescale differences[6].

The observation of the development processes during iterative tutoring revealed some interesting results. It was shown that motor imagery develops faster than physical action and also that primitives in the lower level develop faster than the sequencing of them in the higher level. These observations correspond to some empirical studies of infant development as described in [5].

Furthermore, it was shown that MTRNN can generate various action plans by combining behavior primitives to achieve desired goal states[7]. Action programs in terms of the initial states are searched such that distal states in imagery VP sequences generated from the initial states can match with the desired goal states. It was shown that such planning can generate even novel combinations of learned episodic sequences.

Recently, we showed that dynamic RNN can learn to imitate stochastic sequences of primitives by self-organizing deterministic chaos internally [17], [18]. Furthermore, it was observed that chaos was self-organized in the higher level network with slow time constant. This result may suggest one possible mechanism accounting for "free decision". We may consider that the free decision of arbitrarily selecting actions in sequences might be originated from deterministic chaos developed in the PFC rather than "noise" added at each moment of selecting actions.

Finally, it should be mentioned that the model achieved more than just compositionality of combining primitives. Elaboration between the slow and the fast dynamics during the learning process enabled quite smooth transitions

between one primitive to another, rather than just connecting discrete objects of primitives. Moreover, the slow dynamics carries contextual information like current counts of cycle times for periodic movements as well as goals of heading. Although this counting of cycle times was sometimes imprecise ( $\pm 1$ ) in our experiment, the transitions never occur in the middle of performing primitives. When combinatorial action sequences can be generated to carry context, produce smooth transitions of the primitives and achieve generalization, the appeared structures are not just compositional but also as fluid and "organic" [8], [5].

### C. Executive controls for rule switching and meta-cognition for confidence

We are interested in how the PFC can handle executive controls of rule switching while monitoring confidence for it because this topic should involve problems that challenge higher cognitive brain mechanisms. To this end, we explored the possible neuronal mechanisms for a rule switching task similar to the Wisconsin card sorting test (WCST) with betting options for own successful action outcomes using neuro-robot simulations[9], [10]. A robot acquires three different behavioral response rules to a stimulus (Fig.3a). The same rule repeats for successive trials, but it can be

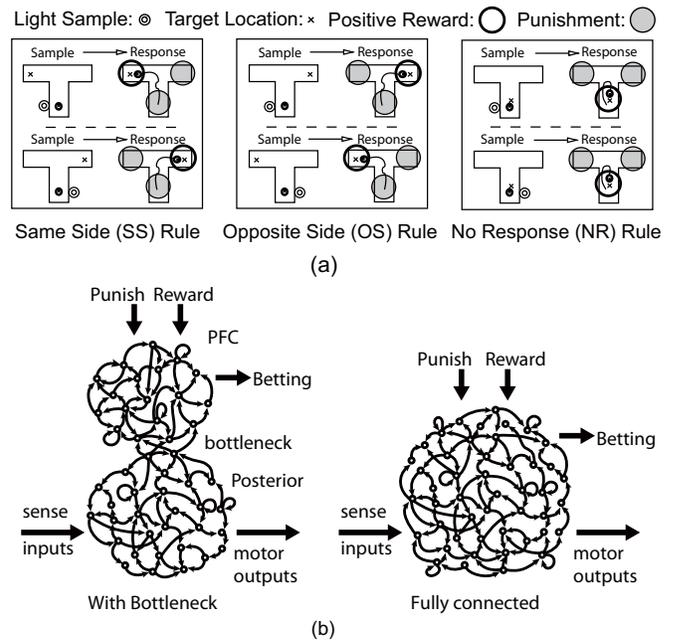


Fig.3 Simulation set up. (a) Three rules were used: the robot should enter the branch on the same side as the light turning on under the "same side" (SS) rule; it should move in the opposite direction under the "opposite side" (OS) rule; and it should remain near the start position independent of the side of the light source in the "no response" (NR) rule. (b) CTRNNs with bottleneck and fully-connected architectures. In the network with a bottleneck, the lower part receives light and range sensor inputs and it outputs motor commands, whereas the higher level receives reward and punishment signals in their corresponding zones and it outputs betting rate. There are no input/output related segregations in the fully-connected case.

changed unpredictably, similarly to an ordinal WCST. The robot is rewarded in the successful trials and punished in the failure trials, and it has to recognize the rule shifts from such feedback. Additionally, the robot can bet on its success at each onset of a trial by outputting an adequate betting rate. The higher the betting rate, the greater the gain (loss) of fitness in the case of success (failure). We employed a CTRNN model with bottleneck connectivity added between the PFC and the posterior parts (Fig.3b). In this model, the time constant of all units are set with the same value. We then compared task performance in cases with and without a bottleneck while keeping the number of neural units the same. The synaptic weights of the networks are modulated in the direction of the larger fitness in the repeated trials during the task acquisition phase by using a genetic algorithm.

The simulation results showed that cases with a bottleneck significantly outperformed those without. This suggests that a certain amount of information segregation between the PFC and the posterior cortex may enhance the task performance. It was observed that three attractors representing three different rules appear in the collective neural activities in the PFC part and that rule switching is achieved by state transition from the current attractor to another as triggered by the punishment signal (Fig.4). It was also observed that the

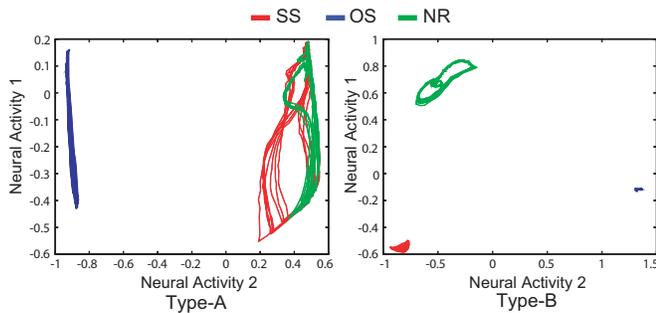


Fig.4 Phase plots of the neural activity generated in Type-A and Type-B cases. The axes are the two principal components of populations in the higher level. The attractor corresponding to each rule is drawn with a different color. In Type-A, some overlaps appear between SS and OS plots because of the similarity in their rules. On the contrary three attractors appear as distinct ones in Type-B.

betting is generated by achieving adequate mapping from this neural state. If the neural state is within one of the attractors which is following the current rule correctly, the betting rate is mapped to the higher values, and otherwise to the lower values, which indicates that each basin of the attractor becomes the region of the high confidence generated with correct executions of the rule. This could be a general mechanism for realizing executive control for rule switching since only this type of dynamic mechanism was found to be self-organized in multiple runs of simulations with a simple, general network model described. Furthermore, a nontrivial finding of this study was that attractor-based encoding by evolution produced two types of rule representation: an analogical representation (Type-A) that incorporates similarity between rules, and a distinct representation (Type-B) for the same set of rules (Fig.4). The qualitative difference in

the geometrical arrangements of the attractors in these two types of rule representation causes different levels of stability in rule execution, which results in different meta-cognitive characteristics of self-confidence about the rules. This may account for the everyday psychological observation that we sometimes acquire rules as tacit knowledge (Type-A) and at other times as explicit, symbolic knowledge (Type-B).

## REFERENCES

- [1] Tani J., Ito M., "Self-organization of behavioral primitives as multiple attractor dynamics: A robot experiment", *IEEE Trans. on SMC. Part A*, Vol. 33, No. 4, pp. 481-488, 2003
- [2] Tani J., Ito M., Sugita Y., "Self-organization of distributedly represented multiple behavior schemata in a mirror system: Reviews of robot experiments using RNNPB", *Neural Networks*, Vol. 17, pp. 1273-1289, 2004
- [3] Ito M., Noda K., Hoshino Y., Tani J., "Dynamic and interactive generation of object handling behaviors by a small humanoid robot using a dynamic neural network model", *Neural Networks*, Vol. 19, pp. 323-337, 2006
- [4] Yamashita Y., Tani J., "Emergence of functional hierarchy in a multiple timescale neural network model: a humanoid robot experiment", *PLoS Computational Biology*, Vol. 4, Issue. 11, e10002200, 2008
- [5] Nishimoto R., Tani J., "Development of hierarchical structures for actions and motor imagery: a constructivist view from synthetic neuro-robotics study", *Psychological Research*, Vol. 73, pp. 545-558, 2009
- [6] Paine R.W. and Tani J., "How hierarchical control self-organizes in artificial adaptive systems", *Adaptive Behavior*, Vol. 13, No. 3, pp. 211-225, 2005
- [7] H. Arie, T. Endo, T. Arakaki, S. Sugano, J. Tani, "Creating novel goal-directed actions at criticality: a neuro-robotic experiment", *New Mathematics and Natural Computation*, Vol. 5, No. 1, pp. 307-334, 2009
- [8] J. Tani, R. Nishimoto, R.W. Paine, "Achieving 'organic compositionality' through self-organization: Reviews on brain-inspired robotics experiments", *Neural Networks*, Vol. 21, pp. 584-603, 2008
- [9] Maniadakis M., Tani J., "Acquiring rules for rules: neuro-dynamical systems account for meta-cognition", *Adaptive Behavior*, Vol. 17, No. 1, pp. 58-80, 2009
- [10] Maniadakis M., Trahanias P. and Tani J., "Self-organizing neural mechanisms for higher-order cognitive functions in human prefrontal cortex", Submitted
- [11] J. Namikawa and J. Tani, "Learning to imitate stochastic time series in a compositional way by chaos", *Neural Networks*, in press
- [12] J. Tani, "Autonomy of Self at criticality: The perspective from synthetic neuro-robotics", *Adaptive Behavior*, Vol. 17, No. 5, pp. 421-443, 2009
- [13] I. Igari and J. Tani, "Incremental Learning of Sequence Patterns with a Modular Network Model", *Neurocomputing*, Vol. 72, pp. 1910-1919, 2009
- [14] J. Tani and M. Ito, "Self-organization of behavioral primitives as multiple attractor dynamics: a robot experiment", *IEEE Trans. on Sys. Man and Cybern. Part A*, Vol. 33, No. 4, pp. 481-488, 2003
- [15] J. Tani and M. Ito and Y. Sugita, "Self-organization of distributedly represented multiple behavior schemata in a mirror system: reviews of robot experiments using RNNPB", *Neural Networks*, Vol. 17, pp. 1273-1289, 2004
- [16] J. Tani, "On the interactions between top-down anticipation and bottom-up regression", *Frontiers in Neurobotics*, Vol. 1, 2007
- [17] J. Namikawa and J. Tani, "A model for learning to segment temporal sequences, utilizing a mixture of RNN experts together with adaptive variance", *Neural Networks*, Vol. 21, pp. 1466-1475, 2008
- [18] J. Namikawa and J. Tani, "Learning to imitate stochastic time series in a compositional way by chaos", *Neural Networks*, in press

# Group B: Research Report

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## I. RESEARCH BRIEF

Animal skillful behaviors emerge through dynamical interactions between brain, nervous system, and musculoskeletal system. So far, biomechanical studies have investigated the mechanical and dynamical characteristics of animal behaviors and neurophysiological studies have examined neural activities and evaluated their functional roles. They individually conduct their studies. This group consists of biologists who study exercise physiology and engineers who study biomechanics and robotics and conduct cooperative research. They use constructive approach toward understanding the mechanisms by integrating biomechanics and neurophysiology (System Biomechanics), where they conduct numerical simulations by constructing anatomically based whole-body musculoskeletal model and neurophysiologically based nervous system model and develop robots to investigate in the real world. This group aims to clarify not only the functional roles of information processed in various nervous systems but also the design principles to produce the mechanical systems, “soft machinery”, which adapt themselves to environmental variations.

## II. RESEARCH ORGANIZATION

This group consists of planned and subscribed research groups. The research subject of each group is as follows:

- B01-01 Neuronal mechanisms of generating and selection of adaptive behaviors (Kaoru Takakusaki, Asahikawa Medical College)
- B01-02 Exploration of the principle mechanism of generating adaptive locomotion on the basis of neurophysiological findings (Naomichi Ogihara, Keio University)
- B01-03 Realization of adaptive locomotion based on dynamic interaction among the body, brain, and environment (Koh Hosoda, Osaka University)
- B01-11 Reflex walk modeling for physically changed person (Hiroshi Yokoi, University of Electro-Communications)
- B01-12 Study on brain adaptation using rat-machine fusion systems and multifunctional neural electrodes (Takafumi Suzuki, The University of Tokyo)
- B01-13 Analysis of relation between neuronal coding and body movement using BMI (Yoshio Sakurai, Kyoto University)
- B01-14 Exploration of reinforcement learning and motivation mechanism in the brainstem-midbrain-basal ganglia circuits (Yasushi Kobayashi, Osaka University)
- B01-15 Neural correlates of muscle synergy in hand movement (Kazuhiko Seki, National Institute for Physiological Sciences)

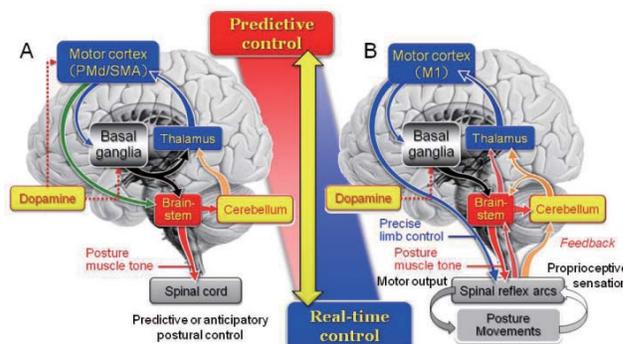


Fig. 1. Neural mechanisms of predictive and real-time motor control

- B01-16 Movement control by the basal ganglia (Atsushi Nanbu, National Institute for Physiological Sciences)
- B01-17 Quantitative evaluation of movement disorders in muscle space for patients with cerebellar degeneration or Parkinson’s disease (Shinji Kakei, Tokyo Metropolitan Organization for Medical Research)
- B01-18 Understanding of adaptive mechanisms of gait by combining neuroimaging, electrophysiology and computational methods (Takashi Hanakawa, National Center of Neurology and Psychiatry)

## III. RESEARCH ACHIEVEMENT

This report shows the representative studies of this group. Further details are shown in the report of each subgroup.

*A. Regulation of muscle tone during movements at the level of spinal cord (B01-01 Kaoru Takakusaki, Asahikawa Medical College)*

This group aimed at elucidating the mechanisms of integration of postural and locomotor synergies. To initiate locomotion, predictive postural control based on cognitive information is essential. During ongoing locomotion, real-time postural control depending on sensory signals from mechanoreceptors is also required. Therefore understanding neuronal mechanisms of “predictive” and “real-time” postural controls is essential to artificially construct “adaptive locomotive system”. In this group, attempts have been made to examine integrate mechanisms of posture and locomotion in the various areas in the central nervous system using neurophysiological, neuropharmacological and molecular genetics assessments in various mammalian animal models. Our findings suggest that cortico-reticular and cortico-cerebellar systems are involved in the “predictive postural control”, and a loop with cerebral cortex cerebellum and spinal cord including muscle tone control system may play major role in the “real-time postural control”(Fig. 1). The basal ganglia may contribute to both controls via projections

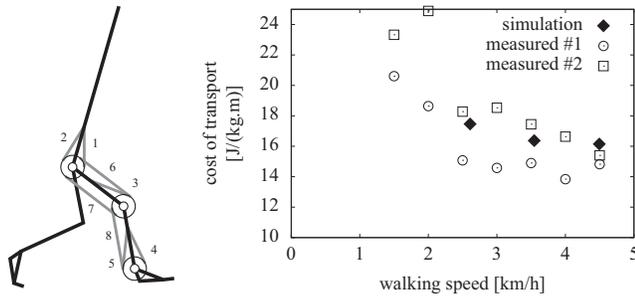


Fig. 2. 2D musculoskeletal model of the Japanese macaque and comparisons of simulated and experimentally obtained mass-specific cost of transport of bipedal walking in Japanese macaque

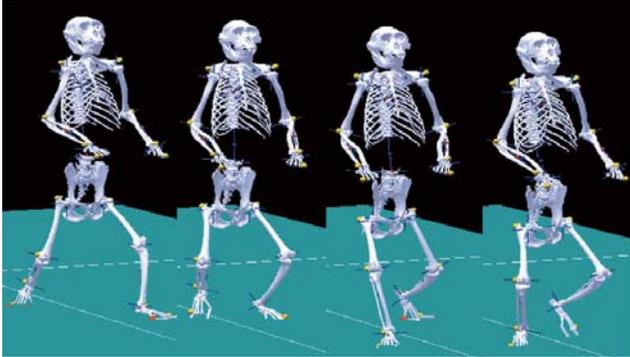


Fig. 3. 3D simulation of bipedal walking of the Japanese macaque

to the cerebral cortex and the brainstem. Neuromodulators including dopamine and orexin are possibly responsible for steady-state regulation of the nervous system.

#### B. Locomotion analysis using musculoskeletal model (B01-02 Naomichi Ogihara, Keio University)

Animals are capable of generating locomotion adaptive to diverse environments by coordinately controlling complex musculoskeletal systems. In order to understand mechanisms underlying the emergence of such intelligent adaptive behavior during locomotion, the mechanisms of information processing emerging from appropriate dynamic interactions among the neuro-control system, musculoskeletal system and environment must be thoroughly investigated. This group has been biomechanically analyzing adaptive locomotor phenomena observed in actual bipedal locomotion in the Japanese monkey (*Macaca fuscata*) using an anatomical whole-body musculoskeletal model. It is demonstrated that the mass-specific metabolic cost of transport decreased as speed increased in bipedal walking of the Japanese macaque, unlike the U-shaped relationship seen in human walking (Fig. 2). Furthermore, the experimentally observed pattern of vertical fluctuations in the body's center of mass was suggested to actually contribute to energy savings via an inverted pendulum mechanism, although the utilization of this mechanism was limited due to anatomical constraints imposed on the musculoskeletal system. We launched a constructive study of locomotion by integrating physiological findings from the locomotor nervous system and the anatomy and biomechanics of the musculoskeletal system, with the

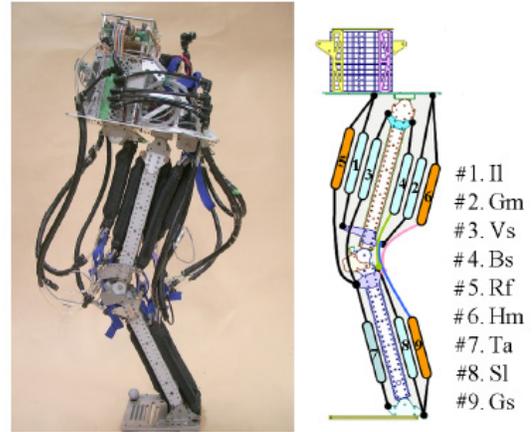


Fig. 4. A jumping robot with anthropomorphic muscular skeleton structure. Muscles #1 (iliacus) and #2 (gluteus maximus) are monoarticular muscles driving the hip joint. Muscles #3 (vastus lateralis) and #4 (popliteus) drive the knee and muscles #7 (tibialis anterior) and #8 (soleus) drive the ankle joint, respectively. Muscles #5 (rectus femoris), #6 (hamstring muscles) and #9 (gastrocnemius) are biarticular muscles that drive not only one but also two joints.

aim of illuminating the dynamic principles underlying the emergence of adaptive locomotion in animals (Fig. 3).

#### C. Realization of adaptive locomotion based on dynamic interaction between body, brain, and environment (B01-03 Koh Hosoda, Osaka University)

An animal has complicated structure consisting of many bones connected with muscles and ligaments that works antagonistically and/or synergistically. Redundancy provided from such complicated mechanism effectively contributes to the hierarchical system consisting of a lower layer devoted to rhythm generation and a higher layer devoted to purposive behavior. This group develops robots driven by artificial pneumatic muscles and clarify the contribution of the joint elasticity on the adaptive locomotion. (1) Biped robot with biarticular muscles. A biped robot with biarticular muscles is developed to investigate their roles on dynamic locomotion (Fig. 4). We conducted jumping experiment from standstill, landing experiment, and bouncing experiment to investigate the role of the biarticular muscles. (2) A feasibility study on stability of gait patterns with changeable body stiffness using pneumatic actuators in a quadruped robot. A quadruped robot with pneumatic artificial muscles is developed. The muscle tone of the robot on the pitching motion at the trunk is changeable by using the changeable elasticity of the pneumatic actuators. The stability of quadruped locomotion in walk and trot patterns with changeable body stiffness was evaluated with numerical simulations and hardware experiments. (3) Realization of snake-like locomotion and observation of a real snake. We develop a snake-like robot and several sensors required for the adaptive locomotion and analyze influence of viscoelasticity on locomotion performance. As the result, very simple control can exhibit three types of locomotion (lateral undulation, sidewinding, and rectilinear) smoothly.

# B01; Neuronal mechanisms of initiation and selection of adaptive locomotor behaviors - with reference to the “Predictive” and “Real-time” postural control -

Kaoru Takakusaki<sup>1</sup>, Futoshi Mori<sup>2</sup>, Katsumi Nakajima<sup>3</sup>, Dai Yanagihara<sup>4</sup>, Taizo Nakazato<sup>5</sup>, Kenji Yoshimi<sup>5</sup>, Shigeru Kitazawa<sup>5</sup>, Masahiko Inase<sup>3</sup>, Kiyoji Matsuyama<sup>6</sup>, Yoshimasa Koyama<sup>7</sup>, Toshikatsu Okumura<sup>8</sup>.

**Abstract:** To initiate locomotion, predictive postural control based on cognitive information is essential. During ongoing locomotion, real-time postural control depending on sensory signals from mechanoreceptors is also required. Therefore understanding neuronal mechanisms of “predictive” and “real-time” postural controls is essential to artificially construct “adaptive locomotive system”. In the present study, attempts have been made to examine integrate mechanisms of posture and locomotion in the various areas in the central nervous system using neurophysiological, neuropharmacological and molecular genetics assessments in various mammalian animal models. Our findings suggest that cortico-reticular and cortico-cerebellar systems are involved in the “predictive postural control”, and a loop with cerebral cortex cerebellum and spinal cord including muscle tone control system may play major role in the “real-time postural control”. The basal ganglia may contribute to both controls via projections to the cerebral cortex and the brainstem. Neuromodulators including dopamine and orexin are possibly responsible for steady-state regulation of the nervous system.

## I. INTRODUCTION

We have faced serious aged society, which increases the numbers of patients with brain dysfunction and locomotor disability. The Mobiligence project aims at understanding the mechanisms of adaptive behaviors and artificially constructing adaptive systems. To generate adaptive locomotive behaviors, we have hypothesized that predictive or anticipatory postural control is required before initiating movements depending on cognitive information and real-time postural control always accompanies with ongoing locomotion depending on sensory signals from mechanoreceptors.

To test the above hypothesis, neuronal mechanisms of locomotor behaviors of mammalian animal models have been examined using neurophysiological, neuropharmacological and molecular genetics assessments. In this report, neuronal mechanisms of generating predictive and real-time postural control are discussed on the basis of results obtained in this 5 years research period.

## II. FRAMEWORK OF LOCOMOTOR CONTROL

Adaptive behaviors require appropriate interaction among the brain, body and circumstance is essential. The expression of the motor behaviors is largely altered by internal states (such as intention, emotion and alertness) of animals and external

circumstances. Figure 1 illustrates basic signal flow involved in locomotor control. Locomotion has been initially considered as emotional behavior that is induced by the projection from the limbic-hypothalamic system to the brainstem [1] (Fig.1B). However, precise stepping movements such as avoiding obstacles resemble to reaching hand movements in higher primates, because these require volitional and cognitive information which are processed by loops with cerebral cortex, cerebellum and the basal ganglia [2, 3, 4] (Fig.1A). Either volitional or emotional, locomotion is accompanied by rhythmic limb movements and adjustment of postural muscle tone. These are automatically regulated by the brainstem and spinal cord [5, 6] (Fig. 1C).

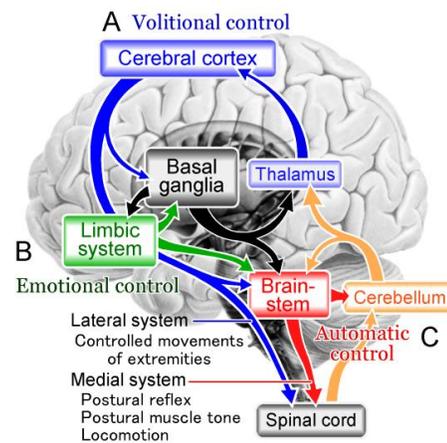


Figure 1 Neuronal pathway involved in volitional (A), emotional (B) and automatic (C) locomotor control

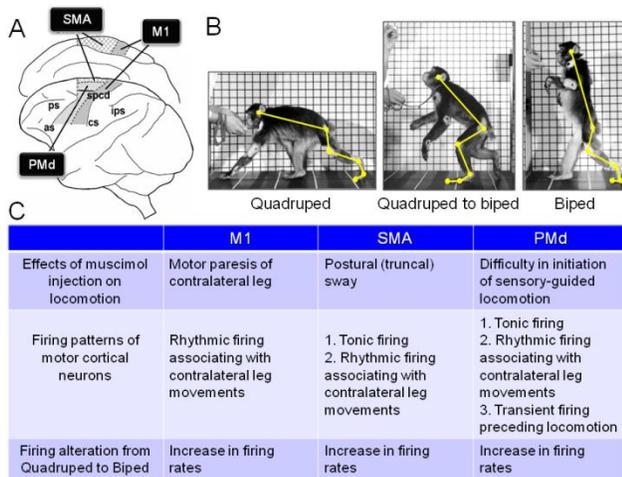
## III. RESULTS

### 1. MOTOR CORTICAL AREAS AND LOCOMOTOR CONTROL

There are several motor areas in the cerebral cortex in monkey (Fig.2A). These are the primary motor cortex (M1), the supplementary motor area (SMA) and the premotor cortex (PM). Then the question is how cortical neurons in these areas contribute to the locomotor behaviors. Nakajima, Mori and Inasse first microinjected muscimol (GABA<sub>A</sub>-receptor agonist) into these areas and alteration of locomotion was examined in monkey who learned bipedal walking on the moving treadmill (Fig.2B). When muscimol was injected into leg and foot areas of the M1, hemi-paralyses was observed in the contralateral leg and foot. On the other hand, muscimol injections into the bilateral SMA resulted in truncal sway or postural disturbance without obvious leg paralyses. When muscimol was injected into the dorsal premotor area (PMd), while monkey could start to walk volitionally, the monkey had a difficulty in visually-guided locomotion (Fig.2C).

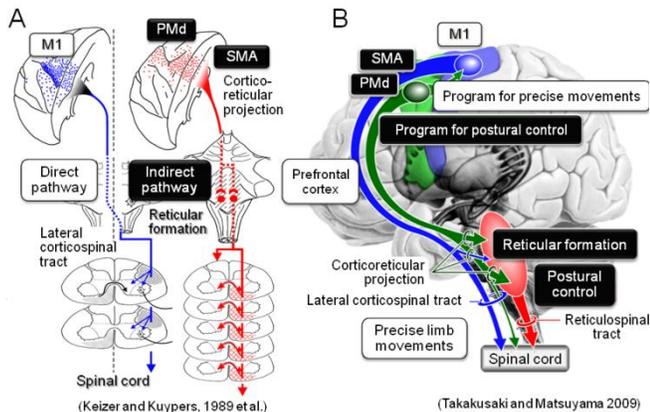
Next, they studied firing property of cortical neurons during treadmill locomotion with quadruped (Qp) and biped (Bp) (Fig.2C). Most M1 neurons had rhythmic firing property which

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**Figure 2 Role of motor cortical areas for quadruped and biped locomotor behaviors**

corresponded to the contralateral leg movements. In contrast, majority of SMA neurons displayed tonic firing rather than rhythmic firing. In addition to tonic and rhythmic firing neurons, the PMd had a particular type of neurons whose firing preceded the onset of locomotion. Moreover, rhythmic and tonic firing neurons in each area exhibited higher discharge rates during Bp locomotion than Qp locomotion.



**Figure 3 Role of corticospinal and cortico-reticulospinal systems on posture and locomotor control**

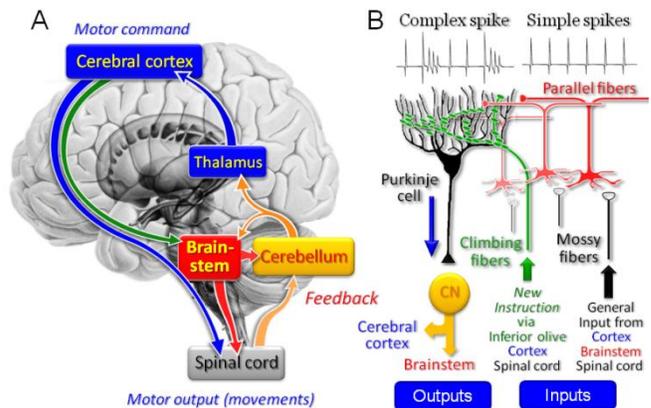
A neuroanatomical study [7] has shown that corticospinal tract arising from M1 projects to the contralateral spinal cord (direct pathway), while cortical neurons from the SMA and the PMd project to the brainstem reticular formation which, in turn, activate reticulospinal neurons (indirect pathway) (Fig. 3A). Based on the present findings together with the anatomical findings, following discussion can be made. (1) Functional topography exists in the motor cortex with respect to the locomotor control; M1 contributes to the contralateral limb movements, SMA contributes to postural control, and the PMd may be also involved in the initiation of locomotion. (2) Cortical contribution is larger in Bp than Qp locomotion. (3) The SMA and the PMd may produce programs of both postural control and precise limb movements. The former can be sent to the reticular formation via corticoreticular projection and further to the spinal cord via reticulospinal tract. The latter may be sent to the M1 and to the spinal cord via lateral corticospinal tract (Fig.3B). (4) Accordingly, motor programs generated at

the cerebral cortex may include information of predictive postural control.

## 2. CEREBELLAR MICROCIRCUITS AND LOCOMOTOR CONTROL

The cerebellum contributes not only to regulation of movements but to motor learning (motor memory) via loops with the cerebral cortex, brainstem and spinal cord (Fig.4A) [8]. There are two sources of inputs to the cerebellum; one is the mossy fibers and the other is climbing fibers. The former maintains Purkinje cell excitability via numbers of parallel fibers to evoke simple spikes, and the latter alters Purkinje cell firing patterns from simple spikes to complex spikes (Fig.4B). Output from the Purkinje cells modulates excitability of the cerebral cortex and the brainstem via cerebellar nuclei (Fig.4B).

Motor command signals from the motor cortex (efferent copy), which are sent to the cerebellum via mossy and climbing fibers, are compared with the results of the movements which are sent as sensory feedback via spinocerebellar tract. The cerebellum calculates the difference between these two signals and sends compensating signals to the cortex and the brainstem so that the movements can be precisely regulated and learned. Then the question is how the cerebellar microcircuits (Fig.4B) contribute to the locomotor control.



**Figure 4 Input to and output from the cerebellum**

Yanagihara designed to examine how mossy and climbing fiber systems contribute to control locomotion using various types of cerebellar dysfunction mice models (Table 1). These are as follows. (1) SCA-transgenic mice, an animal model of Type-3 spinocerebellar disease, has atrophic cerebellum and cerebellar function is totally disturbed. (2) Ho15J mice, in which  $\delta 2$  glutamatergic receptor is knockout, have a failure in synaptic transmission from parallel fibers to Purkinje cells. (3) In Cerebelline-1 knockout mice, function of parallel fibers is disturbed. (4) To disturb climbing fiber system in mice, inferior olivary nucleus was pharmacologically lesioned.

SCA-3 transgenic mice displayed lower trunk position, hyper-flexion of knee joint and grounding of ankle joint during stance phase, indicating that postural muscle tone was reduced (hypotonia). During swing phase, the mice excessively lifted their hand and foot with hyper-flexion limb position.

Ho15J mice and Cerebelline-1 knockout mice displayed hypotonia with enhanced hyper-flexion of limb position. In contrast inferior olivary nucleus lesioned mice even displayed excessive limb-lifting during swing phase without obvious hypotonia. In particular, the mice lifted their hand and foot up to extraordinary height when they overstepped the obstacles during locomotion.

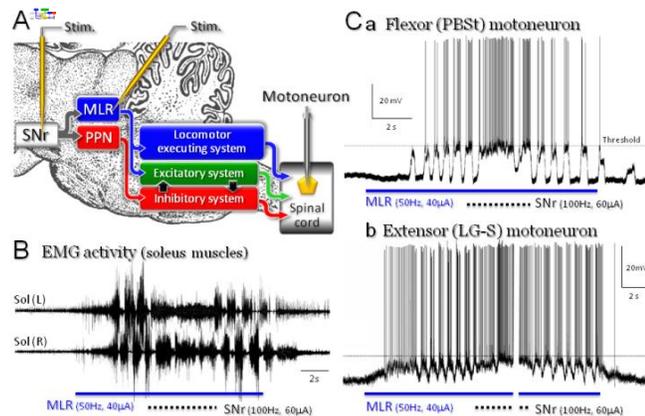
	SCA-3 knockout mice	Ho 15J mouse	Inferior olivary nucleus lesion	Cerebellin 1 knockout mice
Cerebellar dysfunction	Cerebellar function is totally disturbed	Synaptic deficiency between parallel fibers and Purkinje cells	Climbing fiber deficiency	Parallel fiber deficiency
Hypotonia	+++	++		++
Hyper-flexion of limb joints in swing phase	++	+++	+	+++
Hyper-metric limb movements	++	++	+++	++
Small cadence	+	+	+++	+

**Table 1 Cerebellar deficiency mouse model and locomotion**

These findings suggest that (1) hyper-flexion of limb position can be induced by deficiency in mossy and climbing fiber systems, (2) mossy fibers contribute to maintain postural muscle tone and regulation of locomotion using feedback signals, and (3) climbing fibers can be involved in the feed-forward control of limb movements during locomotion using cognitive visuomotor processing.

### 3. BASAL GANGLIA CONTROL OF MOVEMENT AND POSTURE

The basal ganglia contributes to volitional and cognitive movement processing by acting cerebral cortex, postural and locomotor control by acting the brainstem and expression of emotional behaviors by acting the limbic system [9]. Because basic mechanisms of controlling locomotion and posture are located in the brainstem-spinal cord, Takakusaki et al. [4, 10] examined role by the projection from the basal ganglia to the brainstem in the integrative process of posture and locomotion.



The decerebrate cat maintains reflex standing posture due to decerebrate rigidity. In the cat midbrain, there are midbrain locomotor region (MLR) and muscle tone inhibitory region in the pedunculopontine tegmental nucleus (PPN). These nuclei receive GABAergic inputs from the substantia nigra pars reticulata (SNr), an output nucleus of the basal ganglia (Fig. 5A). Repetitive electrical stimuli (50 Hz) applied to the MLR first increased muscle tone (as can be seen in bilateral soleus muscles) and elicited stepping or locomotive activity (Fig.5B). Then stimulation of the SNr with 100 Hz stopped rhythmic stepping movements without reduction of muscle tone. When SNr stimulation was terminated, stepping reappeared.

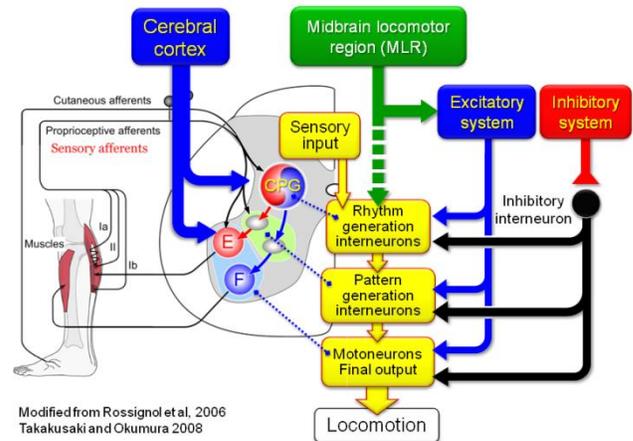
Then excitability of  $\alpha$ -motoneurons that innervate skeletal muscles was examined. MLR stimulation generated rhythmic firing in flexor and extensor motoneurons (Fig.5C). However the rhythmic nature was blocked by the SNr stimulation; the motoneurons were depolarized with tonic firing, indicating that locomotion was prevented with higher level of muscle tone of extensor and flexor muscles, leading to muscle co-contraction.

Next we studied how SNr stimulation controlled muscle tone. Coerulospinal tract arising from the locus coeruleus (LC) is one of muscle tone excitatory systems. Short train pulses of stimuli applied to the LC induced EPSPs in motoneurons. The same type of stimuli was applied to the PPN, an origin of muscle tone inhibitory system, induced IPSPs in motoneurons. When conditioning stimuli (100Hz) were applied to the SNr, LC-induced EPSPs were enhanced and PPN-induced IPSPs were greatly attenuated. These findings suggest that the basal ganglia can modulate muscle tone; an increase in the basal ganglia output induces hypertonus by enhancing excitatory system's activity and attenuating inhibitory system's activity.

Accordingly an increase in the basal ganglia output to the brainstem may reduce locomotor activity and lead to muscle co-contraction so that limb joint stiffness can be increased to stabilize posture when locomotive activity is terminated.

### 4. LOCOMOTOR CONTROL BY THE MUSCLE TONE CONTROL SYSTEMS IN THE BRAINSTEM AND SPINAL CORD

Neuronal elements in the spinal reflex arcs constitute spinal locomotor networks (Fig.6). Central pattern generator (CPG) is composed of interneurons mediating flexion reflex. Rhythmic signals generated in the CPG are sent to locomotor pattern generating neurons. They are last-order interneurons including reciprocal Ia interneuron (reciprocal inhibition), Ib interneuron (autogenic inhibition) and Renshaw cells (recurrent inhibition). The locomotor pattern signals are finally sent to motoneurons to evoke muscle contraction. These spinal locomotor networks are located in the cervical and lumbosacral spinal segments.



Modified from Rossignol et al, 2006  
Takakusaki and Okumura 2008

**Figure 6 Spinal locomotor network and supraspinal control**

Takakusaki and Matsuyama studied neuronal mechanisms of controlling locomotion at the brainstem and spinal cord. Descending signals from MLR activate the spinal locomotor network via reticulospinal neurons which longitudinally innervate whole spinal neuraxis to generate steady rhythmic locomotor movements [6, 12]. Proprioceptive sensory inputs from skin, joints and muscles act on interneurons and motoneurons so that they provide real-time modulation of locomotor movements as shown in Fig.6. Motor command signals descending in lateral corticospinal tract from motor cortex acts on the spinal locomotor network so that precise limb movements can be achieved when intentional locomotor control is needed.

Muscle tone inhibitory system arising from the PPN modulates locomotion by attenuating excitability of sensory afferents, interneurons and  $\alpha$ -,  $\gamma$ -motoneurons. Muscle tone excitatory systems including coerulo-, raphe-, vestibulo- and

(excitatory) reticulo-spinal tracts also modulate locomotion by acting interneurons and motoneurons (Fig.6).

Consequently, real-time postural and locomotor control can be realized by the interaction between descending motor signals (from the cerebral cortex, locomotor center and muscle tone control systems) and peripheral proprioceptive sensations. In particular, (1) descending signals from the cerebral cortex contribute to the modification of intentional gait control, (2) signals from the MLR steadily generate locomotor rhythm and pattern, and (3) signals from muscle tone control systems simultaneously modulate the excitability of sensory afferents, interneurons and motoneurons so that appropriate level of muscle tone that matches with on-going locomotor movements can be determined.

### 5. LIMBIC-HYPOTHALAMIC SYSTEM AND MODULATION OF LOCOMOTION AND MUSCLE TONE

The limbic system is involved in the expression of emotional behavior, which is often exemplified as “fight or flight reaction”. Locomotion is one of the emotional behaviors. Emotional signals usually increase muscle tone and/or elicit locomotion. However emotional stimuli often elicit “cataplexy”, which is characterized by muscle tone suppression that resembles to muscular atonia during REM sleep in narcolepsy patients. Because subcortical areas including limbic system and the basal ganglia are active during REM sleep, muscular atonia can be evoked even in wakefulness in narcolepsy. Accordingly, it can be hypothesized that limbic-brainstem pathway is capable of evoking either locomotion or muscular atonia. Orexinergic neurons broadly project to most of the areas in the central nervous system (CNS). Fibers and terminals are particularly dense in the midbrain including the substantia nigra, PPN, LC and the area corresponding to the MLR. Because orexinergic neurons are degenerated in narcolepsy, Takakusaki, Okumura and Koyama designed to understand how orexinergic system contributes to control of locomotion and muscle tone [11]. Findings obtained from neurophysiological studies in decerebrate cats suggest that orexinergic projections to the MLR and LC facilitated locomotion and increased muscle tone, respectively. On the other hand, orexinergic projections to the PPN and the SNr suppressed the activity of muscle tone inhibitory system.

As shown in Fig.7A, excitability of locomotion executing system and muscle tone excitatory system is higher, but that of the muscle tone inhibitory system is lower in the presence of

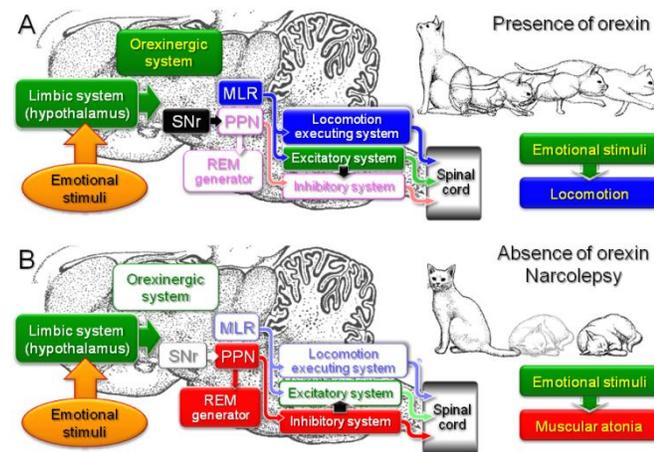


Figure 7 Orexinergic modulation muscle tone and locomotion

orexin (normal). Therefore emotional stimuli preferentially excite locomotion executing system and excitatory system so that the stimuli elicit locomotion. However in the absence of orexin (narcolepsy), identical emotional stimuli resulted in muscular atonia because the excitability of the inhibitory system is higher than that of the locomotor system and the excitatory system (Fig.7B). Therefore the emotional stimuli may selectively activate any systems that have preferentially higher excitability [10].

### 6. REWARD AND DOPAMINERGIC SYSTEM

Although dopaminergic (DA) system is one of monoaminergic systems, it is different from serotonergic and noradrenergic systems because the DA system projects to the limited areas; the basal ganglia (motor and cognition), limbic system (emotion and memory) and the prefrontal cortex (planning and sociality). The DA operates as reward system so that this system plays critical roles in expression of adaptive behaviors. Yoshimi, Nakazato and Kitazawa started to detect DA release using *in vivo* voltammetry for understanding neuronal mechanisms of acquisition of reinforcement learning process.

In the task in which reward was expected, DA neurons of alert monkey fired within 300 ms after presentation of reward cue (Fig.8C) [9]. Because DA neurons project to the basal ganglia, diamond-electrode for catecholamine current detection was inserted into the caudate nucleus (Fig.8A). An increase in current was detected when reward cue was

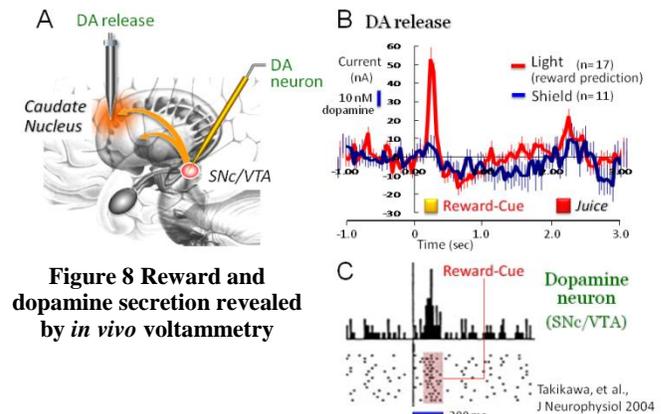


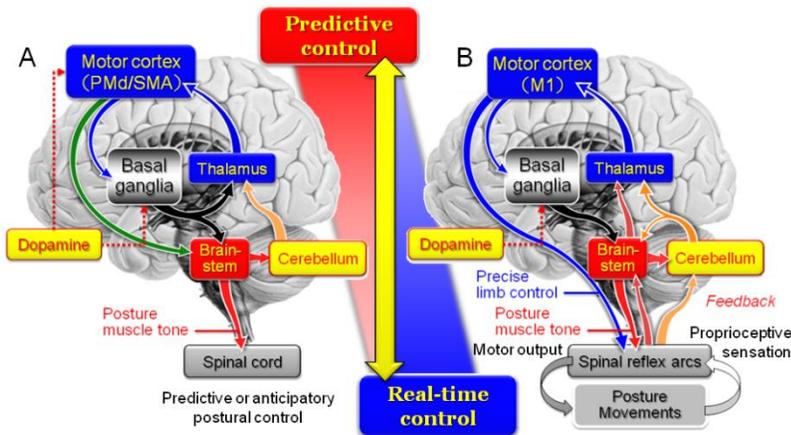
Figure 8 Reward and dopamine secretion revealed by *in vivo* voltammetry

presented, and its time course quite resembled to that of firing of DA neurons (Fig.8 B and C). Because the presentation of the reward cue did not evoke current when the vision was shielded, the current were judged as DA current due to release of DA (Fig.8B).

Now temporal resolution of the current detection became extremely precise and the accuracy of the resolution adequately reflects temporal resolution of firing of DA neurons. The great advance of this technique will provide large contribution of understanding the neuronal mechanisms of acquisition of adaptive behaviors depending on DA release in the basal ganglia, limbic system and prefrontal cortex during reinforcement learning

### IV. DISCUSSION

Postural control always precedes any movements. Because environment always altered, postural control for generating goal-directed movements is inevitably “predictive”. On the other hand, automatic and adaptive postural control during



**Figure 9 Neural mechanisms of Predictive and Real-time motor control**

on-going movements requires real-time postural control depending on the alteration of sensory information. Therefore both “predictive or anticipatory postural control” and “real-time postural control” are inevitably needed for acquisition of adaptive locomotor behaviors (Fig.9).

### 1. “PREDICTIVE MOTOR PROGRAMS” ARE PRODUCED BY LOOPS OF THE CEREBRAL CORTEX WITH THE CEREBELLUM AND THE BASAL GANGLIA

The SMA and the PMd receive abundant inputs from the prefrontal cortex and parietal cortex. The former provides information of motor plans and the latter provides somatosensation and spatial information. The SMA/PMd produces motor programs based on these inputs. The basal ganglia and the cerebellum contribute to this motor programming. In particular, findings in this study suggest that dopaminergic modulation of the basal ganglia function and climbing fiber systems for modulating cerebellar function play crucial roles in the motor programming process.

Motor programs include both “postural control program” and “precise limb movement program”. Cortico-reticular projection arising from the SMA/PMd may provide postural control program to the brainstem reticular formation so that predictive or anticipatory postural control can be realized via brainstem-spinal cord descending tracts, including the muscle tone excitatory and inhibitory systems, to perform goal-directed movements. Predictive-anticipatory postural control can be realized by the cortico-basal ganglia-cerebellar loops and the cortico-reticulospinal projection systems (Fig.9A).

Frozen gait is observed in patients with Parkinson’s disease and frontal lobe deficiency. Neural network between the SMA/PMd and basal ganglia may therefore contribute to predictive postural control preceding gait onset. Output from the basal ganglia reduces in Huntington’s disease where abnormal posture and involuntary movements are observed. These abnormal movements can be due to insufficient inhibition of unnecessary motor programs in this disease.

### 2. “REAL-TIME MOTOR CONTROL” BY THE BRAINSTEM, SPINAL CORD AND THE CEREBELLUM

The most areas in the CNS are involved in real-time motor control. Real-time control here we define is that it requires

proprioceptive sensory feedback signals from skin, joints and muscles. In this respect, spinal reflexes have the simplest mechanism of the real-time control. Because locomotor rhythm and patterns are produced by interneuronal networks, proprioceptive sensory signals acting on interneurons contribute to the modulation of locomotor rhythm and pattern. Muscle tone control systems modulate not only muscle tone but also locomotor rhythm and patterns by modulating excitability of sensory fibers, interneurons and motoneurons (Fig.6). Therefore the muscle tone control systems regulate feedback gain of spinal reflexes so that these systems contribute to real-time movement control.

However only spinal reflexes are hard to compensate and retrieve movements based on “motor reference or efference copy of the motor command”. The cerebellum takes this part. One of the characteristics of cerebellar motor control is comparison of efference copy from the motor command and feedback signals as a result of movements. Present findings suggested that mossy fiber deficiency reduced muscle tone and hyper-flexion of limb position, indicating mossy fiber systems in the cerebellar loops with motor cortex and spinal cord are involved in the real-time movement control. On the other hand, mice with climbing fiber deficiency failed in either visual estimation of the object scale, memorizing the scale or drawing proper limb trajectory. Climbing fiber systems in the cerebro-cerebellar loops may thus contribute to programming preparatory or predictive postural control for appropriate limb trajectory using visuomotor information.

### 3. CONTROL OF POSTURE AND MOVEMENT BY THE BASAL GANGLIA

The basal ganglia do not receive sensory inputs. Therefore basal ganglia utilize sensory and cognitive information from sensory and associate cortices in order to participate in the generation of motor program. We have demonstrated that the SMA/PMd have motor programs of both postural control and precise limb movement control, indicating that the basal ganglia contribute to predictive postural and precise movement control via connections with the cerebral cortex. Reinforcement learning, by the action of dopaminergic system on the basal ganglia, limbic system and prefrontal cortex [9], is one of major mechanisms for acquisition of predictive movement control and formation of appropriate motor program. .

The basal ganglia also control posture and locomotion via projections to the brainstem (Fig.9B). Therefore the basal ganglia- brainstem system may also indirectly contribute to real-time feedback movement control by the modulation of muscle tone that regulates the gain of spinal reflexes and sensory signals.

### 4. NEUROMODULATORS AND EXCITABILITY OF THE CNS

Monoaminergic and cholinergic neurons constitute widely spread projection systems and largely alter background excitability of the CNS. Therefore the action of these neuro-

modulators is involved in the regulation of vigilance state (wakefulness and sleep) [10]. Orexinergic and monoaminergic (serotonergic and noradrenergic) systems enhance the activity of muscle tone excitatory system during wakefulness. In contrast, cholinergic system activates muscle tone inhibitory system and suppresses postural muscle tone during REM sleep. Accordingly these widespread projection systems may operate as state-modulators to alter excitability of the CNS so that state-dependent behaviors can be appropriately expressed in accordance with vigilance states [10]. Cataplexy in narcolepsy patients is now interpreted as the abnormal expression of emotional behaviors elicited by emotional stimuli [11].

#### REFERENCES

- [1] S. Grillner, A.P. Georgopoulos, L.M. Jordan, "Selection and initiation of motor behavior". In: Stein, P.S.G., Grillner, S., Selverston, A.I., Stuart, D.G. (Eds.), *Neurons, Networks, and Motor Behavior*, MIT Press, Boston, pp. 3-19, 1997.
- [2] A.P. Georgopoulos, S. Grillner, "Visuomotor coordination in reaching and locomotion", *Science*, vol. 245, pp. 1209-1210, 1989.
- [3] F.A. Middleton, P.L. Strick, "Basal ganglia and cerebellar loops: motor and cognitive circuits", *Brain Res. Rev.*, vol. 31, pp. 236-250, 2000.
- [4] K. Takakusaki, "Forebrain control of locomotor behaviors", *Brain Res. Rev.*, vol. 57, pp. 192-198, 2008.
- [5] S. Grillner. The motor infrastructure: from ion channels to neuronal networks. *Nat. Rev. Neurosci.*, 4, 573-586, 2003
- [6] K. Takakusaki, T. Okumura. "Neurobiological Basis of Controlling Posture and Locomotion" *Adv. Robot.* 22; 1629-1663, 2008.
- [7] K. Keizer, H.J.G.M. Kuypers, "Distribution of corticospinal neurons with collaterals to the lower brain stem reticular formation in monkey (*Macaca fascicularis*)", *Exp. Brain Res.*, vol. 74, 311-318, 1989.
- [8] S. M. Morton, A. J. Bastian, "Mechanisms of cerebellar gait ataxia", *Cerebellum*, vol. 6, pp. 79-86, 2007.
- [9] O. Hikosaka, Y. Takikawa, R. Kawgoue, "Role of the basal ganglia in the control of purposive saccadic eye movements", *Physiol. Rev.* vol. 80, pp. 954-978, 2000.
- [10] K. Takakusaki, K. Saitoh, S. Nonaka, T. Okumura, N. Miyokawa, Y. Koyama, 2006. "Neurobiological basis of state-dependent control of motor behavior", *Sleep Biol. Rhyth.*, vol. 4, pp. 87-104. 2006
- [11] K. Takakusaki K, K. Takahashi K, K. Saitoh, et al. Orexinergic projections to the midbrain mediate alternation of behavioral states from locomotion to cataplexy. *J Physiol.* 568: 1003-1020, 2005.
- [12] S. Rossignol, R. Dubuc, J-P. Gossard, "Dynamic sensorimotor interactions in locomotion", *Physiol. Rev.*, vol. 86, pp. 89-154, 2006.
- [13] D.A. McCreary, I.A. Rybak, "Organization of mammalian locomotor rhythm and pattern generation", *Brain Res. Rev.* 57, 134-146, 2006.

# System biomechanics of bipedal walking in the Japanese macaque: Exploration of principal mechanism for adaptive locomotion

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**Abstract:** Animals are capable of generating locomotion adaptive to various environments by coordinately regulating complex musculoskeletal system. To elucidate mechanisms underlying the emergence of intelligent adaptive locomotion in animals, we launched a constructive study of locomotion in the Japanese macaque. Herein we introduce achievements of our system biomechanics study of bipedal locomotion in the Japanese macaque in the past four years.

## 1. INTRODUCTION

Animals are capable of generating locomotion adaptive to diverse environments by coordinately controlling complex musculoskeletal systems. In order to understand mechanisms underlying the emergence of such intelligent adaptive behavior during locomotion, the mechanisms of information processing emerging from appropriate dynamic interactions among the neuro-control system, musculoskeletal system and environment must be thoroughly investigated.

Towards this goal, we launched a constructive study of locomotion by integrating physiological findings from the locomotor nervous system and the anatomy and biomechanics of the musculoskeletal system, with the aim of illuminating the dynamic principles underlying the emergence of adaptive locomotion in animals. Particular focus was placed on analyzing and modeling bipedal locomotion in the Japanese macaque (*Macaca fuscata*), as Japanese macaques have recently been used for neurophysiological studies on adaptive locomotor mechanism, allowing direct comparisons between experimental data and simulation results. Moreover, the transition from quadrupedalism to bipedalism in Japanese monkeys is regarded to some extent as a modern analogue of the evolution of bipedal locomotion and therefore offers an interesting subject for research in the field of physical anthropology [1-5].

Herein we introduce the results and achievements of our system biomechanics study of bipedal locomotion in the Japanese monkey in the past four and a half years.

## 2. WHOLE-BODY ANATOMICAL MODEL

We constructed a three-dimensional whole-body musculoskeletal model of the Japanese macaque based on computed tomography (Fig. 1) [6]. The skeleton was divided into the following bone segments: head, thorax, lumbus, pelvis, scapula, humerus, ulna, radius, hand (carpals and metacarpals), femur, tibia (with fibula), and foot (tarsals and metatarsals). Each joint was approximated as a combination of hinge joints,

joint centers and rotational axes estimated by joint morphology based on joint surface approximation using a quadric function. A kinematic skeleton of the Japanese macaque was thus mathematically described as a chain of 20 links connected by revolute joints. The total number of DOFs for the skeletal system was 47. As a result of morphologically accurate description of the joint kinematics based on quadric function approximation, rotational axes of the joints did not coincide with bone coordinate axes, unlike robots or conventional biomechanical models.

The fresh cadaver of a Japanese macaque was dissected to mathematically describe the path of each muscle and its associated capacity to generate force. Each muscle in the fore- and hindlimbs was carefully exposed and the points of origin and insertion were observed. The muscle was then removed and mass and fascicle length were systematically recorded to calculate physiological cross-sectional area. The path of each muscle was defined using a series of points connected by line segments.

The constructed biologically relevant model serve as a useful tool for comprehensive understanding of the design principles of the musculoskeletal system and the control mechanisms for locomotion in the Japanese macaque.

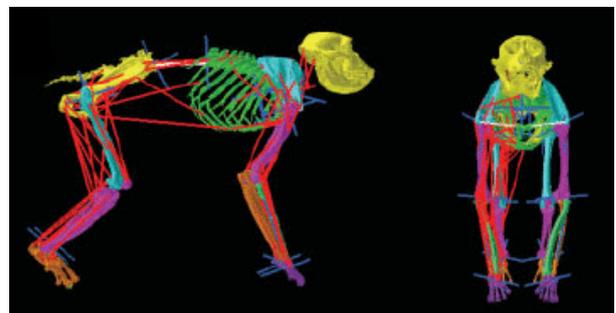


Fig. 1 Whole-body musculoskeletal model of the Japanese macaque.

### 3. KINEMATICS OF BIPEDAL WALKING

We performed a kinematic analysis of bipedal locomotion on highly trained Japanese macaques and calculated three-dimensional angular motions of hindlimb and trunk segments based on a model-based registration method [7].

Two highly-trained, performing Japanese macaques walking bipedally on a treadmill at 3, 4, and 5 km/h were filmed using 4 high-speed cameras (Fig. 2) and locomotor kinematics were analyzed by digitizing markers attached at joints and calculating coordinates of markers. If the above musculoskeletal model of the Japanese macaque could be matched to the temporal history of digitized marker coordinates, all body skeletal motions could be reconstructed. For this, joint angles were adjusted frame-by-frame so as to minimize 1) the sum of distances between each motion-captured marker and the corresponding marker on the model and 2) deviations of joint angles from the anatomically natural position, while 3) satisfying kinematic constraints due to the clavicle. The results showed that the proposed model can successfully reconstruct and visualize anatomically reasonable, natural musculoskeletal motion of the Japanese macaque during locomotion (Fig. 3). Using the estimated 3D kinematics, we calculated mean displacement profiles of the center of mass (COM) at three different speeds for the two macaques, and subsequently instantaneous potential and kinetic energies of the COM.

Our results demonstrated a considerable degree of

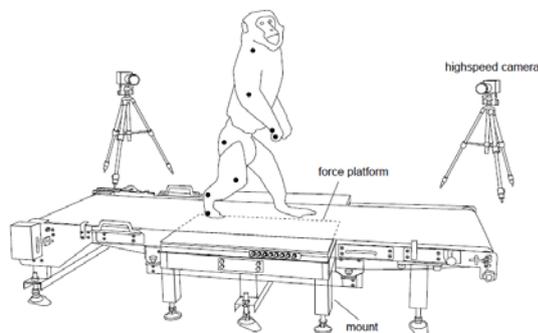


Fig. 2 Kinematic analysis of bipedal walking. A Japanese macaque walking on a treadmill was filmed using 4 highspeed cameras.

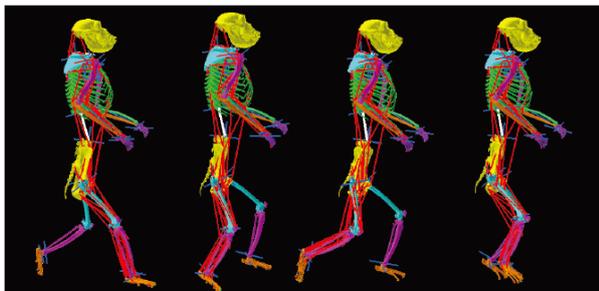


Fig. 3 Reconstructed whole-body musculoskeletal kinematics of bipedal walking using a model-matching method.

axial rotation occurring at trunk and hip joints during bipedal walking, suggesting that bipedal walking in Japanese macaques is essentially three-dimensional. In addition, ranges of angular motions at hip and ankle joints were larger and the knee joint was more flexed in the mid-stance phase with increasing walking speed, indicating that gait kinematics are modulated depending on walking speed. Furthermore, macaques were confirmed to have actually acquired, at least to some extent, the energy conservation mechanism of walking due to pendular exchange of potential and kinetic energy, but effective utilization of this mutual exchange of energy was found to occur only at comparatively low velocity. The spring-like running mechanics were probably more exploited at higher speed, even though the duty factor was above 0.5. Fundamental differences in bipedal strategy seem to exist between human and non-human primate bipedal locomotion.

### 4. GROUND REACTION FORCE

To clarify whether trained monkeys generate a two-peaked force profile similar to humans, as well as to better characterize the dynamics of their locomotion, we collected their ground reaction force profiles (Fig. 4) [8]. Trained and ordinary monkeys walked across a force platform set in a wooden walkway at a self-selected speed.

Typically, non-human primates, including Japanese macaques, generate a single-peaked force curve when they walk bipedally. Our results demonstrated that the trained monkeys also generated a single-peaked vertical ground reaction force profile; human-like double peaks were not observed. However, the shape of the force curve differed between the two groups; the force curve was relatively trapezoidal or parabolic in the ordinary monkeys and relatively triangular in the trained monkeys and the timing of the vertical peak was shifted towards early stance phase.

Oscillatory motions of the COM calculated based on the measured force curves suggested that the trained monkeys were able to induce greater fluctuations in the vertical ground force than ordinary monkeys by shifting the timing of generating peak vertical force towards early stance phase (Fig. 4). However, the vertical COM displacement in the trained monkeys was found to be highest in the late-stance phase just before foot contact, unlike human normal walking, suggesting that the energetic advantage based on the inverted pendulum mechanism is limited in the Japanese macaque. In bipedal walking, hip muscles such as the psoas major and tensor fasciae latae are stretched, particularly at the time of toe-off when the hip is most extended. This restriction in the range of hip joint motion seems to prevent Japanese macaques from generating effective push off, and consequently, generation of human-like walking is quite impossible for an inherently quadrupedal primate. Morphological preadaptation of hip joint mobility is therefore a fundamental determinant of the acquisition of humanlike bipedal

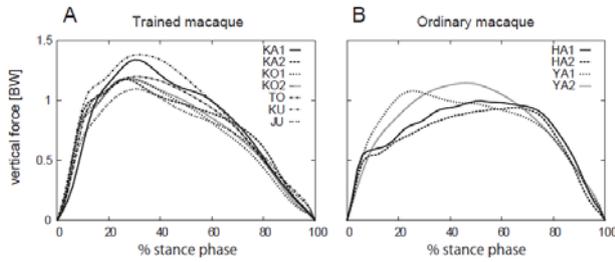


Fig. 4 Vertical ground reaction forces for a single bipedal-walking step. The curves were averaged out per subject. (A) trained, (B) ordinary macaques. Forces were normalized by body weight (BW).

walking.

## 5. SIMULATION OF BIPEDAL WALKING

We dynamically reconstructed bipedal walking of the Japanese macaque to investigate causal relationships among limb kinematics, speed and energetics, with a view to understanding the mechanisms underlying the evolution of human bipedalism [9]. We constructed a 2D musculoskeletal model of the bipedal Japanese macaque consisting of seven links representing the HAT (head arms and trunk), thighs, shanks and feet, and eight principal muscles based on the above whole-body musculoskeletal model (Fig. 5). To generate bipedal walking, desired joint trajectories of bipedal walking were created by averaging measured kinematic data, and trajectories of the desired muscle length were generated. We used the desired muscle length profile to generate the activation pattern of each muscle. The motor command sent to the muscles was generated using two oscillators and a PD feedback control law.

Using this framework, we evaluated the effects of changes in cycle duration and gait kinematics on locomotor efficiency in the Japanese macaque. The energetic cost of locomotion was estimated based on the calculation of mechanical energy generated by muscles. Our results demonstrated that the mass-specific metabolic cost of transport decreased as speed increased in bipedal walking of the Japanese macaque, unlike the U-shaped relationship seen in human walking (Fig. 5). Furthermore, the experimentally observed pattern of vertical fluctuations in the body's center of mass was suggested to actually contribute to energy savings via an inverted pendulum mechanism, although the utilization of this mechanism was limited due to anatomical constraints imposed on the musculoskeletal system.

We have also tried to make our 3D whole body model walk in a computer. Although multiple steps were successfully generated (Fig. 6), further investigations are necessary for practical use.

## 6. PHASE RESETTING

Modulation of locomotor rhythm based on phase-resetting may greatly contribute for generation of adaptive locomotion in animals including humans. We

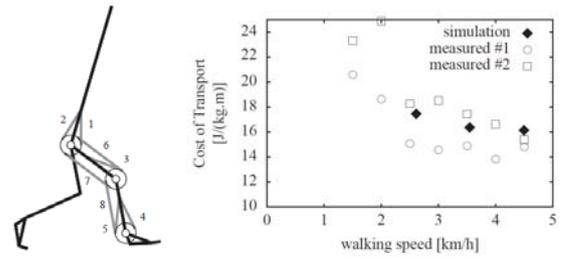


Fig. 5 2D musculoskeletal model of the Japanese macaque and comparisons of simulated and experimentally obtained mass-specific cost of transport of bipedal walking in Japanese macaque.

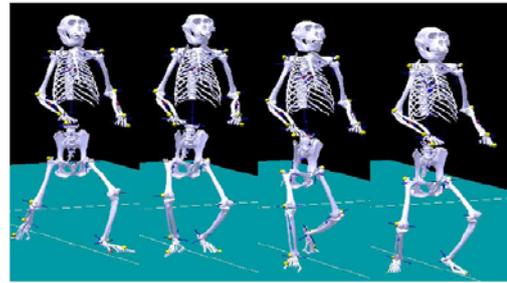


Fig. 6 3D simulation of bipedal walking of the Japanese macaque.

therefore investigated contribution of phase-resetting on generation of robust bipedal locomotion using a 2D human musculoskeletal model. The skeletal model consists of seven rigid links with nine principal muscles. The nervous system model consists of the central pattern generator (CPG) represented by the two-layered hierarchical networks of the rhythm generator (RG) and pattern formation (PF) networks. The RG was modeled by a set of phase oscillators that produces basic rhythm of locomotion and the phase was reset based on foot-contact information. The PF model then generated the spatiotemporal patterns of the muscle activation based on the rhythm input.

Initially, we constructed the PF model based on the prescribed joint kinematics and a feedback control [10]. The simulation results demonstrated that phase-resetting contributes to improving the robustness against force disturbances. However, in this simulation based on a feedback control, we must have assumed unrealistically high values for the gain parameters. Furthermore, the system was obviously destabilized if we introduce transport delays in the nervous system.

Therefore, we next proposed a more physiologically based mathematical model. Here we assume that basic muscle activation patterns are prescribed in the spinal cord level to form feedforward muscle activity for locomotion. Therefore, the PF was modeled to generate muscle activities based on the combination of five prescribed basic rectangular pulses (Fig. 7) [11]. We incorporated the posture control based on the trunk pitch and the COM velocity.

When we used only the feedforward signals, the walking model could not establish steady walking and

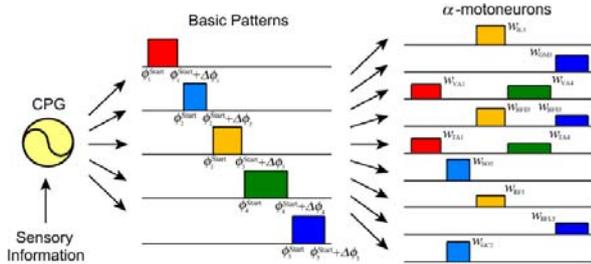


Fig. 7 Five basic activation patterns prescribed in the spinal cord level to form feedforward muscle activity.

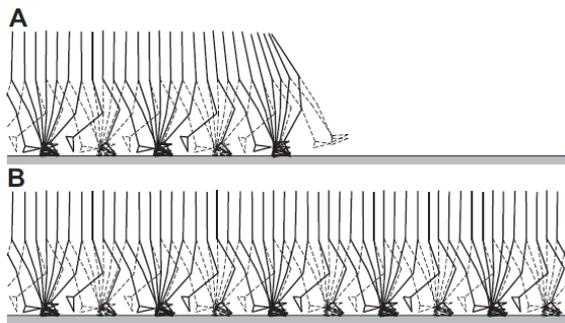


Fig. 8 Simulated walking patterns using only feedforward signals (A) and incorporating feedforward signals, posture control, and phase resetting (B).

fell over. However, it achieved steady walking by integrating the feedforward signals, posture control, and phase resetting (Fig. 8). To investigate the robustness of the generated locomotion, we added external perturbations by changing trunk mass or slope angle. Our results demonstrated that the phase resetting does actually improve the robustness of locomotion against perturbations. Incorporating feedforward control and sensory regulation mechanisms based on neurophysiological findings allowed us to successfully emulate adaptive bipedal locomotion.

## 7. CONCLUSION

Herein we report our system biomechanics studies of bipedal locomotion in the Japanese monkey (see also [12]). Although we have made significant progress in understanding mechanisms underlying the emergence of adaptive locomotion, the complete mechanisms are yet to be clarified. We will further investigate the dynamic principles of adaptive locomotion by analyzing the behavior of neuro-musculoskeletal dynamics from a system engineering perspective.

We wish to express our gratitude to all the staff at the Suo Monkey Performance Association for their generous collaborations in the experiments. This study was supported by a Grant-in-Aid for Scientific Research on Priority Areas "Mobiligence" from MEXT, Japan.

## REFERENCES

[1] S. Hayama, M. Nakatsukasa & Y. Kunimatsu, "Monkey performance: The development of

bipedalism in trained Japanese monkeys", *Acta Anatomica Nipponica*, Vol. 67, pp. 169-185, 1992.  
 [2] E. Hirasaki, N. Ogihara, Y. Hamada, H. Kumakura, & M. Nakatsukasa, "Do highly trained monkeys walk like humans? A kinematic study of bipedal locomotion in bipedally trained Japanese macaques", *Journal of Human Evolution*, Vol. 46, pp. 739-750, 2004.  
 [3] M. Nakatsukasa, N. Ogihara, Y. Hamada, Y. Goto, M. Yamada, T. Hirakawa & E. Hirasaki, "Energetic costs of bipedal and quadrupedal walking in Japanese Macaques", *American Journal of Physical Anthropology*, Vol. 124, pp. 248-256, 2004.  
 [4] N. Ogihara, H. Usui, E. Hirasaki, Y. Hamada & M. Nakatsukasa, "Kinematic analysis of bipedal locomotion of a Japanese macaque that lost its forearms due to congenital malformation", *Primates*, Vol. 46, pp. 11-19, 2005.  
 [5] M. Nakatsukasa, E. Hirasaki & N. Ogihara, "Energy expenditure of bipedal walking is higher than that of quadrupedal walking in Japanese macaques", *American Journal of Physical Anthropology*, Vol. 131, pp. 33-37, 2006.  
 [6] N. Ogihara, H. Makishima, S. Aoi, Y. Sugimoto, K. Tsuchiya & M. Nakatsukasa, "Development of an anatomically based whole-body musculoskeletal model of the Japanese macaque (*Macaca fuscata*)", *American Journal of Physical Anthropology*, Vol. 139, pp. 323-338, 2009.  
 [7] N. Ogihara, H. Makishima, & M. Nakatsukasa, "Three-dimensional musculoskeletal kinematics during bipedal locomotion in the Japanese macaque reconstructed based on an anatomical model-matching method", *Journal of Human Evolution*, in press.  
 [8] N. Ogihara, E. Hirasaki, K. Kumakura & M. Nakatsukasa, "Ground-reaction-force profiles of bipedal walking in bipedally trained Japanese monkeys", *Journal of Human Evolution*, Vol. 53, pp. 302-308, 2007.  
 [9] N. Ogihara, S. Aoi, Y. Sugimoto, K. Tsuchiya & M. Nakatsukasa, "Forward dynamic simulation of bipedal walking in the Japanese macaque: investigation of causal relationships among limb kinematics, speed, and energetics of bipedal locomotion in a non-human primate", submitted.  
 [10] S. Aoi, N. Ogihara, Y. Sugimoto & K. Tsuchiya, "Simulating adaptive human bipedal locomotion based on phase resetting using foot-contact information", *Advanced Robotics*, Vol. 22, pp. 1697-1713, 2008.  
 [11] S. Aoi, N. Ogihara, T. Funato, Y. Sugimoto & K. Tsuchiya, "Evaluating functional roles of phase resetting in generation of adaptive human bipedal walking based on a physiologically based model of the spinal pattern generator", submitted.  
 [12] Y. Sugimoto, S. Aoi, N. Ogihara, & K. Tsuchiya, "The Stabilizing function of mus-culoskeletal system for periodic motion", *Advanced Robotics*, Vol.23, pp. 521-534, 2009.

# Group B-3: Realization of Adaptive Locomotion based on Dynamic Interaction between Body, Brain, and Environment

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Kosuke Inoue (Ibaraki University), Takashi Takuma (Osaka Institute of Technology)  
Hiroshi Kimura (Kyoto Institute of Technology)

**Abstract**— The research goal of group B-3 is to establish Bio-Robotics methodology, in which hypotheses for generating adaptive behavior is developed by observing biological system and they are verified from the constructivist view point. Focusing on locomotion, we realized adaptive locomotive control consisting of a rhythmic controller based on reflexes and CPG and a regulatory controller that modulates the interaction between the body and its environment. We suppose that muscular-skeletal structure of a biological system plays a crucial role for realizing such adaptive control. To support this supposition we realize three types of locomotive robots, biped, quadruped, and snake-like robots, out of muscular-skeletal structure, and conduct experiments.

## I. INTRODUCTION

One of main goals of robotics to reproduce adaptability of biological system, but realized robots are surprisingly poor yet. To realize biological system-like adaptability, we not only take hints by observing the real biological systems, but understand underlying principles, learn from its mechanical/physiological structure, and build up a new paradigm for designing adaptive robots, which we call “Bio-Robotics”.

Through the project, we have been applying hypotheses obtained from biology, biomechanics, and physiology, and testing their validity/effectiveness through the constructivist view point, and further, trying to establish Biorobotics methodology. Especially, we stand on the proposition that adaptive locomotion can be realized by combination of a rhythmic controller based on reflexes and CPG and a regulatory controller that modulates the interaction between the body and its environment. We suppose that muscular-skeletal structure of a biological system plays a crucial role for realizing such adaptive control. To support this supposition we realize three types of locomotive robots, biped, quadruped, and snake-like robots, out of muscular-skeletal structure, and conduct experiments.

## II. MUSCULAR-SKELETON SYSTEM AND MOBILIGENCE

The muscular-skeleton structure plays an essential role for realizing adaptive locomotion. Especially, if we build a hybrid controller consisting of a rhythmic controller based on reflexes and CPG and a regulatory controller that modulates the interaction between the body and its environment, it has great advantage over traditional electrical motors. It can enable to implement “preflex” without time-delay, which is supposed to be crucial for realizing adaptive locomotion.

On the other hand, a pneumatic artificial muscle has a number

of defects, hysteresis, time-delay between driving and its movement, and non-linearity. In total, it is relatively hard to control a pneumatic muscle, and therefore, researchers tend to avoid using it. We dare to use such pneumatic muscles so that we introduce new paradigm for designing adaptive locomotion out of such artificial muscular-skeleton structure. In the following, we introduce the robots, bipeds, a quadruped, and snake robots, and show experimental results to demonstrate effectiveness of the proposed methodology.

## III. BIPED ROBOTS (HOSODA, TAKUMA)

We study two type of bipedal locomotion, walking and jumping. Stable walking is realized by a combination of a ballistic walking controller based on foot touch and a tonus controller that changes walking velocity. Stable and controllable jumping is realized by a combination of monoarticular and biarticular muscles that drives not only one but two joints simultaneously. The mono and biarticular muscles provide driving force and regulatory force, respectively, which basically follows the hypothesis known in biomechanics.

### A. Walking speed control by tuning tonus

When a biped robot is controlled by electric motors, its speed is determined by the given desired trajectory of each joint. However, in human walking, walking speed is emerged by the interaction between body, control, and environment. Especially, the body tonus plays a great role to change the speed. Emergence of walking by such interaction between the body tonus and the environment is supposed to be a key issue for realizing adaptive walking.

We conducted experiments with a biped robot driven by pneumatic artificial muscles (Figure 1) and studied on the relation between walking speed and tonus of the artificial muscles (Figure 2). In Figure 2, we can find that the walking speed changes according to the amount of air to agonistic and antagonistic pneumatic muscles (indicated by  $T_s$  and  $T_e$  in the figure).

### B. Jump behavior modulated by biarticular muscles

Biarticular muscles that drive not only one joint but also multi joints play an important role for realizing synergistic motion of the animal’s body. They also provide redundancy that can be utilized for controlling complex body system. This redundancy can be utilized for roll sharing and cooperation between low and high control layers. We

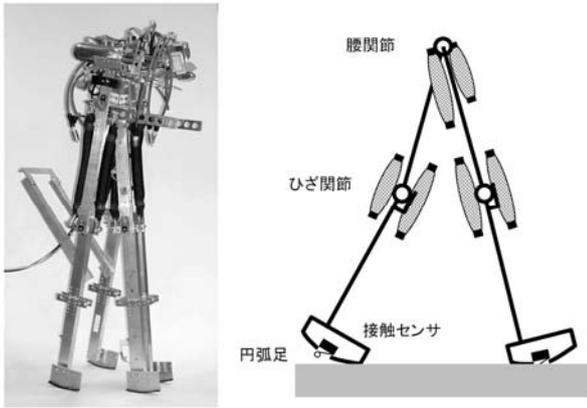


Figure 1: a biped robot driven by pneumatic artificial muscles.

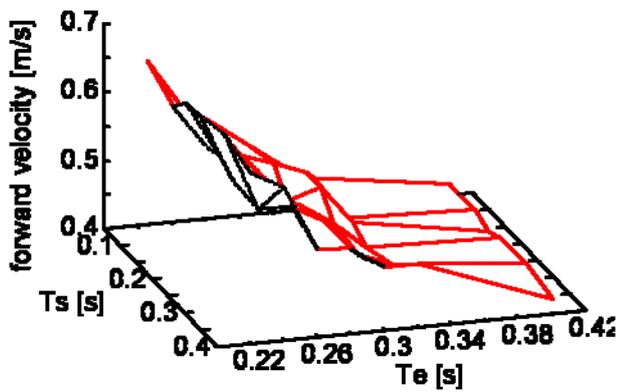


Figure 2: Experimental result: relation between supplying duration to agonistic and antagonistic pneumatic muscles.

constructed a monopod with biarticular muscles and investigate jumping behavior (Figure 3).

The robot is equipped with 3 biarticular muscles: Rectus femoris, Hamstrings, and Gastrocnemius. Each of them regulates the coordination between knee and hip joints and the one between knee and ankle joints. Since the system has these muscles, it can realize coordinated movement between joints. When only the knee is driven by monoarticular muscles, extension of the knee drives ankle joint through the gastrocnemius and hip joint through hamstrings. The synergistic motion depends on designing parameters such as moment arm of the muscles, and in the case of the monopod shown in the figure, such coordinated movement occurs when the biarticular muscles are excited. As a result, the rotation of the robot is suppressed. This is shown in the experimental results (figure 4). The contribution of Rectus femoris and Hamstrings is relatively small to the behavior of the robot, since it has only small torso. We also designed and manufactured a robot with a larger torso that imitates the proportion of a human, and investigated the relation between tension of biarticular muscles and the resultant behavior.

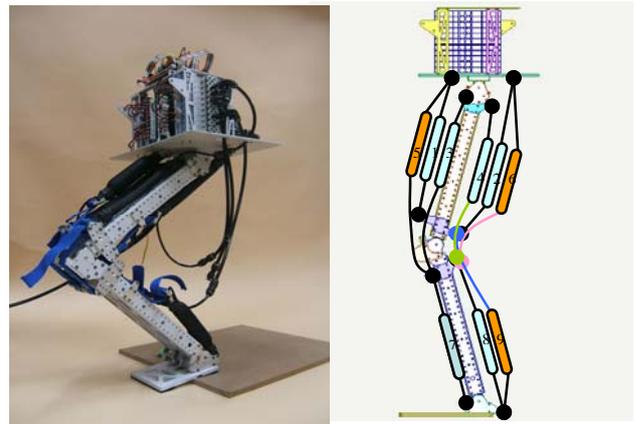
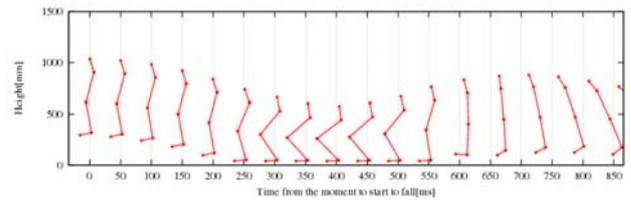
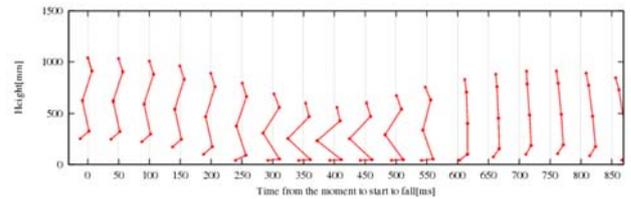


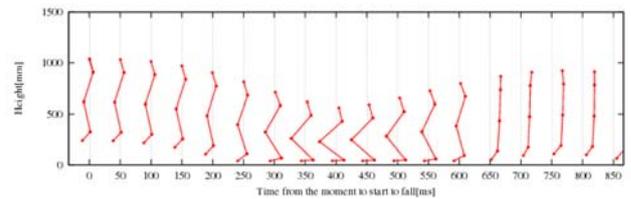
Figure 3: A 2D monopod with biarticular muscles



(a) air supply to gastrocnemius :0ms



(b) air supply to gastrocnemius :10ms



(c) air supply to gastrocnemius :150ms

Figure 4 : bouncing behavior of the monopod when only the knee joint is activated at the contact.

#### IV. QUADRUPED ROBOT (TSUJITA)

We conducted experiments on a quadruped robot to investigate behavior emerged from combination of an oscillator-type gait controller driven by state-resetting and a stiffness controller that modulates the total behavior. We design and develop a quadruped robot driven by pneumatic artificial muscles including trunk joint.

The stability of locomotion also strongly depends on the mechanical properties of the body mechanism, especially the joint stiffness. The muscle tone of the robot on the pitching motion at the trunk is changeable by using the changeable elasticity of the pneumatic actuators. The stability of quadruped locomotion in walk and trot patterns with changeable body stiffness was evaluated with numerical simulations and hardware experiments.

##### A. Tonus of the trunk and gait stability

The model of the robot is shown in Figure 5. All the joints are driven by antagonistic pneumatic artificial muscles. The trunk joint is driven by four pneumatic artificial muscles, and we can change the trunk tonus along pitch and yaw axes.

We modeled the dynamics of the robot, and estimated Poincaré map's eigenvalue at various duty ratio. The result is shown in Figure 6. In the figure, relation between trunk stiffness and maximum eigenvalue is shown with respect to various duty ratios. Note that when duty ratio  $\beta$  is around 0.75 (typical duty ratio for a walk pattern), the locomotion is stable at a low joint stiffness of the trunk. But when duty ratio  $\beta$  is around 0.50 (typical duty ratio for a trot pattern), the locomotion is stable at a high joint stiffness of the trunk. The midrange duty ratio and the joint stiffness are not suitable for stable locomotion. These facts may note that gait transition occurs from a stable attractor to another one by passing through the unstable parameter region. That remains as the future work to clarify.

Figure 7 shows the results of the hardware experiment. It shows locomotion stability vs joint stiffness of the trunk both in the walk and trot patterns. Same as simulation results, we can note that there is an appropriate parameter region in terms of joint stiffness for stable locomotion in each gait pattern. In the case of crawl pattern, if we choose appropriate stiffness at the trunk, the robot can continue its stable walk, but too great stiffness at the bottom actuator leads unstable. To the contrary in the case of trot pattern, enough great stiffness on both actuators makes its locomotion stable but lacking of enough stiffness at the trunk causes unstable locomotion

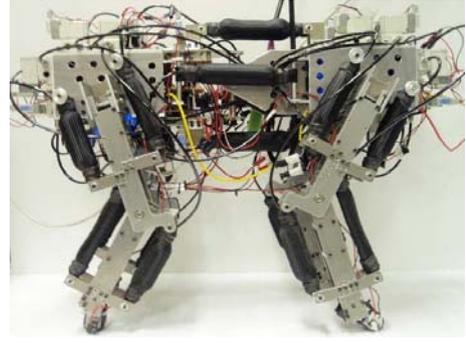


Figure 5: A quadruped robot driven by antagonistic pneumatic artificial muscles

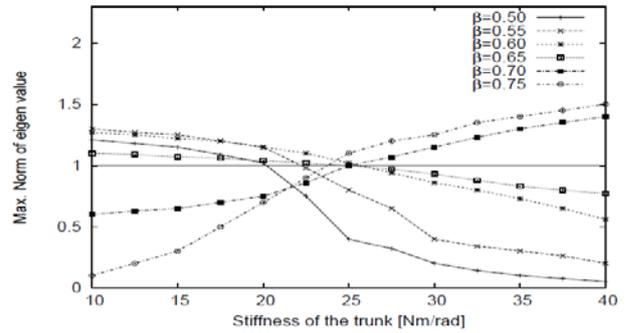


Figure 6: Maximum norm of the Poincaré map's eigen-value at various duty ratio  $\beta$  and trunk joint stiffness.

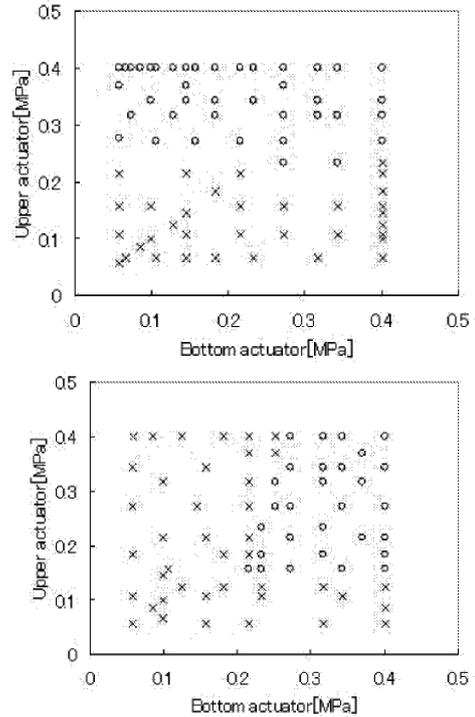


Figure 7: Stability map in quadruped locomotion, crawl (above) and trot (below).

## V. SNAKE-LIKE ROBOT (INOUE)

Snakes can adapt to almost all the terrestrial environment by wriggling their cord-shaped body. We investigated the mechanism underlying their characteristic locomotion pattern aiming at illuminating relationship between the motion pattern and the adaptive functions.

### A. Adaptive meandering locomotion based on CPG model

It is pointed out that a kind of neural system named CPG (central pattern generator) located in spinal cord of animals plays a prominent role for generating and controlling rhythmic body movement. Because it is expected that such a neural system with self-induced oscillation has a dominant effect in a snake meandering on a smooth ground without irregularity, we developed a CPG-based controller for meandering locomotion of a snake-like robot and verified that such a controller can exhibit the locomotion similar to living snakes in simulations and real snake-like robots.

Besides, it is known that parameters of snakes' body movement adaptively changes when the frictional condition between the ventral surface and the ground changes. In this adaptation, information of the reaction force from the ground is expected to be important. In order to achieve the same adaptability, we developed sensors measuring reaction forces received by passive wheels on the ventral surface of the robot. By developing a CPG-based controller with feedback of reaction force from the sensors and optimizing controller parameters, the same adaptation is achieved on the robot.

### B. Development of a "Virtual Snake" Simulator

From the former biological studies and knowledge from animal experiments including dissection and CT-imaging, it became clear that snakes achieves adaptive locomotion by actuating axial muscles that has extremely longer span compared with ordinary mammals. In order to investigate the function of this type of musculoskeletal structure, we constructed a dynamics model of a "virtual snake" in a simulated space using precise shape of skeletal structure, attachment points of tendons and positions of muscle bundles on cross-section of the snake body that are obtained from animal experiments (Figure 8). Through comparative investigation of the locomotion exhibited by the model and in real snakes, knowledge of physical functions of individual muscles or bones and functions of the neural controllers.

### C. Snake-like Robots with artificial muscles

Contribution of viscoelasticity in animals' musculoskeletal system to emergence of adaptability is actively discussed in recent years. As a snake-like robot with such flexible body, we developed a snake-like robot PAS-1 (Figure 9), which has an antagonistic arrangement of pneumatic actuators. PAS-1 has four actuators on the left, right, top and bottom of the central body axis and can demonstrate three dimensional movements.

Differently from the case of electric motors, PAS-1 is expected to achieve smooth movement compliant to its surrounding environment without precise control of joint angle or torque. Therefore, by ON/OFF control of the

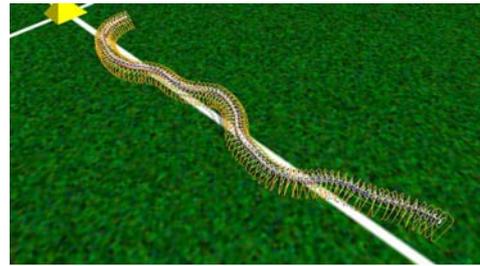


Figure 8: Virtual snake model



Figure 9: A snake-like robot Pas-1

actuators, that is, by opening and closing valves injecting or expelling high-pressure air in the actuators at certain timings, we verified that PAS-1 can achieve smooth locomotion by such simple control when the movement is fast.

Additionally, we developed sensors to measure (1) reaction force from the ground (integumentary sense organ) and (2) length and tension of the actuators (artificial muscle spindles and tendon organs). Using them, we investigated function of spinal neural systems, e.g. reflection, and achieved adaptive movement of the robot with rapid response to the environments.

We further developed a snake-like robot PAS-2 actuated by extremely long multi-articulated artificial muscles based on the precise data of musculoskeletal system obtained by the experiments. The chassis of PAS-2 has four big holes in which muscle bundles go through. PAS-2 has two muscle bundles per one side corresponding to two kinds of muscles (SSP-SP and IC) and each of it includes 7-articulated muscles (One chassis corresponds to three vertebrae of real snakes). Through the development of hardware recapturing musculoskeletal system of living snakes and investigation of its locomotion, perception on the mechanisms of physical interaction between the body structure and the environment in snake-like locomotion mode is expected.

# Reflex walking assist system for paralyzed person

Hiroshi Yokoi, Masatoshi Takita, Kaori Kita

**Abstract**—This report summarizes the results in 2010 of competition subgroup (Yokoi and Takita) at the Scientific Research on Priority Areas "Emergence of Adaptive Motor Function through Interaction between Body, Brain and Environment - Understanding of Mobiligence by Constructive Approach Group B. This research focused on the system development of biofeedback for walking assist of paralyzed person. The research subjects are discrimination of intentions of motion based on epidural signal detection, and reflex walking assisting based on biofeedback by electrical stimulation through surface electrodes. The results are stable characteristics of walking assist system, and high discrimination reliability of intentions of motion.

## I. INTRODUCTION

DISORDER of nervous system causes paraplegic and panplegia takes away human mobility, and decreases Quality of Life (QOL). This research aims at recovering mobility of people with walking difficulties, and try to reveal the sensory-motor system of those people for assuming their motion intention and to build function-recovery scheme shown in Fig.1.

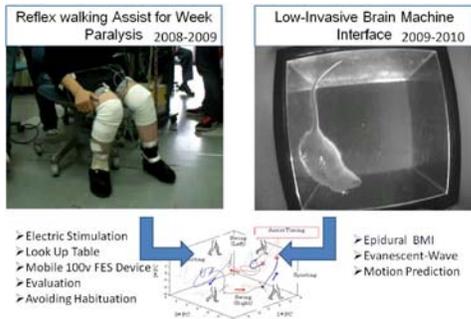


Fig.1 Concept of reflex walking assist based on low invasive BMI

We take two approaches in parallel for solving those issues: a physiological approach to use animals and an engineering approach to build man-machine mutual adaptive system. As a final target, we focus on building a measurement/control system, which

This work was supported in Grant-in-Aid for Scientific Research on Priority Areas "Emergence of Adaptive Motor Function through Interaction between Body, Brain and Environment - Understanding of Mobiligence by Constructive Approach -" from the Japanese Ministry of Education, Culture, Sports, Science and Technology.

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automatically adjust to human sensory-motor system. So, we use a functional electrical stimulator (FES), and examine responses of sensory-motor system in this paper.

## II. DEVELOPMENT OF BIOFEEDBACK FOR WALKING ASSIST OF PARALYZED PERSON

The FES activates muscles and reflexes with electrical stimulations, and is effective to people who has functional peripheral nerves and muscles. That is, the FES functions as the central nerve system to actuate muscles. However, there are various disorders of sensory-motor systems so that the system requires dynamical adaptability to the characteristics of their unique sensory system and usage environments. Thus, we propose our FES system, and the conceptual diagram is shown in fig.2. The main characteristics of this system are to stimulate two different types of targets: muscle and reflex. Therefore, it is necessary to implement assist scheme for its user: that is, we need to reveal the relationship between ways to stimulate and joint movements.

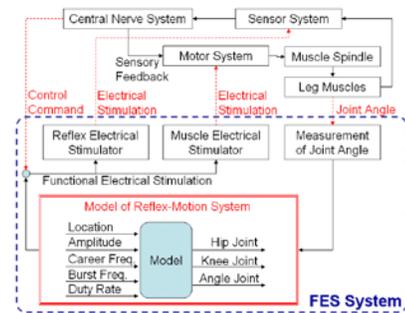


Fig.2. Modeling of Reflex Walk for FES System

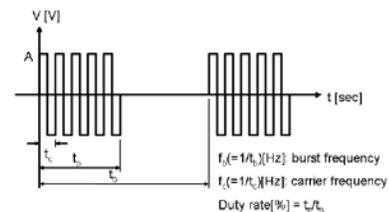
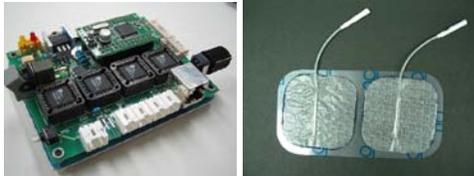


Fig.3. Wave Form of Functional Electric Stimulation

The FES device is shown in Fig.4 (a). It consists of a 16bit microchip controller and analogue switches. The user receives electrical stimulations through electrode pads (shown in Fig.4b), which are attached near target muscles or nerves. The FES generates low-frequent and bipolar-square waves as shown in Fig.3. The user adjusts the following parameters: its amplitude, career frequency, burst frequency, and duty rate, Those parameters are adjustable by its user.



(a) Developed Device (b) Surface Electrode  
Fig.4. FES System

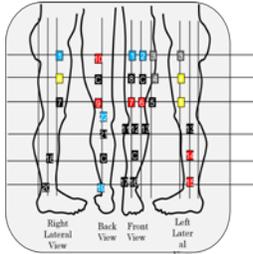


Fig.5. Test position of electrical stimulation



Fig.6. Experimental setting for Reflex Motion

Table 1. Relation among stimulus position to reflex motion

As an experimental result, five motion patterns are obtained for carrier frequencies. Table 1 shows the typical activation of muscle groups. Where, Reflex means reflective motion of joint, Muscle means muscle contraction and joint motion by the direct electrical stimulation, Small means fine muscle contraction, Slow means slow motion of joint rotation lower than 0.8[rad/s], Muscle twitch means joint motion with twitch, No means no response of muscle and joint motion. Fig.5 shows the possible position of electrodes, and Fig.6 shows the scene of experiment for detecting electrical stimulation and joint motion.

No.	Carrier Freq [Hz]	Muscle Contraction	No.	Carrier Freq [Hz]	Muscle Contraction
1	1	Slow	12	1	No
2	1	Slow Reflex Act	13	1	No
3	1	Slow Reflex Act	14	1	No
4	1	Muscle twitch	15	1	No
5	1	No	16	1	No
6	1	No	17	1	No
7	1	No	18	1	Small
8	1	Muscle twitch	19	1	Small
9	1	Slow	20	1	No
10	1	Slow	21	1	No
11	1	No	22	1	No
					Reflex Act

### III. WALKING ASSIST BY REFLEX ELECTRICAL STIMULATION

By using the position and parameters of electrical stimulation, we tested standing up motion and walking assist. The experiments of effect of electrical stimulations are investigated for the positions of electrical stimulation are hip joint ID1 and ID2, behind of knee joint ID6, and outside of ankle joint ID5 shown in Fig.7. We apply the FES for walking assist. For the patient, it is necessary to prevent from scuffing. That is, we aim at bend knee and hip joints during swing phase on the left leg with the FES. The combination of the direct muscle stimulation and the reflex stimulation are applied for the walk assistance. The muscle stimulation was in charge of actuating the ankle joint and the reflex stimulation was in charge of actuating the knee and hip joints. We confirm that the FES assistance

controls the walking speed of the patient. The maximum of the walking speed was similar to the speed of the normal person (Fig.9). Moreover, the patient demonstrated to climb up and down steps with the FES. The paralyzed leg did not scuff the steps as shown in Fig.10.

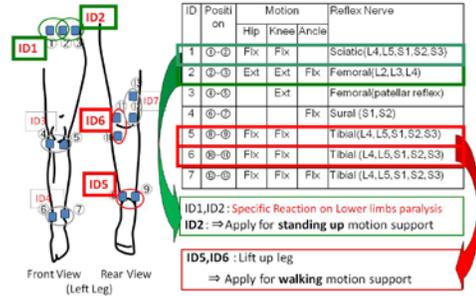


Fig.7. Electrical stimulation position of reflex motion for standing up and walking

For the patients, it takes 5.0 [s] to stand up without the FES, meanwhile, it takes 5.4 [s] to stand up with the FES. That is, the FES assist improve the motion speed 7%. The transitions of joint angles with/without the FES are shown in Fig.8. It is clear that the joint motion with the FES is more smooth than the joint motion without the FES from 1.8 [s] to 5.0 [s].

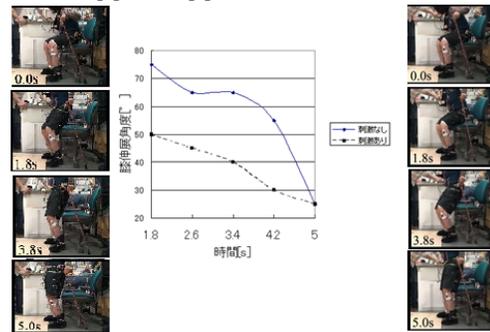


Fig.8. Time series data of knee angle of standing up motion

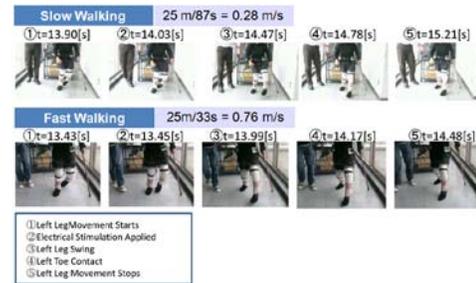


Fig.9. Reflex walking assist for arbitrary speed

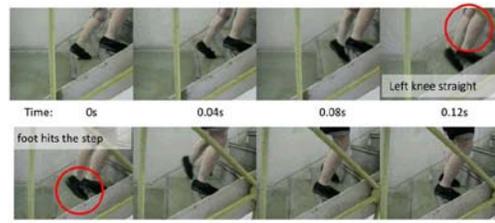


Fig.10. Reflex walking assist for climbing up steps.

The main trouble of electrical stimulation is caused by reaction for the passive input for somatic-sensory area. Since the continuous stimulation derives habituation that disturbs concentration for cognition, it is difficult to have a continuous effect. Next experiment shows brain reaction analyzed by f-MRI for single electrical stimulation in Fig.12. Fig12(a) is a block design of photo shot, where, 1[volume] is TR=5[s], stimulus period is 3[s], rest period is 2[s], and analyzed by 5[volume] × 8 pictures. The parameters of electrical stimulation P1 and P2 are commonly set on electrical voltage, carrier frequency, and duty ratio. But the burst frequencies are set 50Hz of P1 and 100Hz of P2 for each. The result is shown that the reaction of somatic sensory area can be seen for both P1 and P2 stimulation in Fig12 (b), however the reaction is not clear enough to estimate T value.

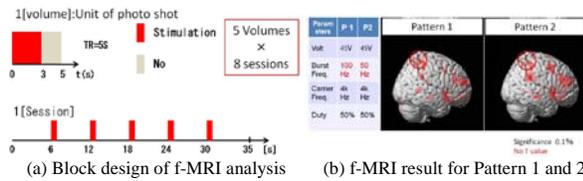


Fig.12. f-MRI analysis for single pattern of electric stimulation

In order to reduce an effect of habituation for continuous input, a continuous input of multiple stimulation patterns, and propose a dynamic pattern of stimulation by a partial change to two kinds of patterns of mixing ratio were optimized. Next experiment shows brain reaction analyzed by f-MRI for mixed electrical stimulation of P1 and P2 in Fig.13. Fig13(a) is a block design of photo shot, where, 1[volume] is TR=5[s], stimulus period is 3[s], rest period is 2[s], and analyzed by 5[volume] × 8 pictures. The parameters of electrical stimulation P1 and P2 are commonly set on electrical voltage, carrier frequency, and duty ratio. But the burst frequencies are set 50Hz of P1 and 100Hz of P2 for each. The mixed stimulation produced by continuous input of P1 and P2 with duty ratio as following: 5:5, 7:3, 8:2, 9:1 for f-MRI analysis. The result shows that the T value of somatic sensory area in the case of 7:3 indicates as maximum, and clear reaction. Therefore, stable stimulation is obtained with this mixture pattern.

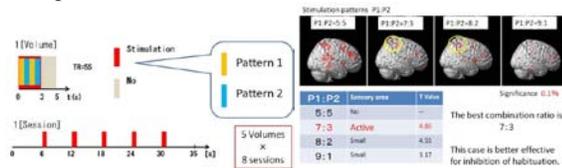


Fig.13. f-MRI analysis for single pattern of electric stimulation

#### IV. LOW INVASIVE BMI

Epidural electrodes placed between the skull and dura mater to record a rat's neural activity for low-invasive BMI (Fig. 13) is proposed. The epidural electrodes do not affect brain immunity because the surgery is restricted to outside the dura mater. In

addition, the spatial resolution of the epidural electrode is thought to be lower than that of the ECoG because of the attenuation and spreading of signals through the dura (Fig.14).

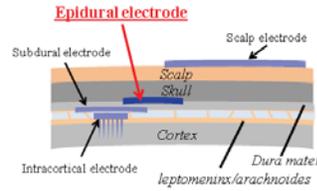


Fig. 13 The locations of an epidural electrode and conventional electrodes for recording cerebrum activities. The names of body tissues are written in italic letter.

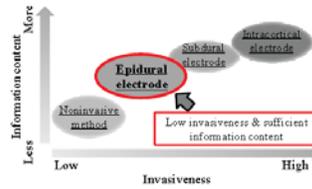


Fig. 14 The concept of epidural electrodes.

If the epidural electrode can capture sufficient information for a practical BMI, it may be a useful lower-invasive alternative method. To show the feasibility of epidural electrodes for BMI, we carried out motion classification that assigns epidural signals to actual locomotion of rat. We employed a pattern recognition method in this study. Specifically, a short-time fast Fourier transform (FFT) was used as the feature extraction for epidural potentials, and a support vector machine (SVM) was used for classification, which assigns the epidural signals to the objective behavior.

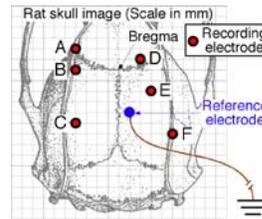


Fig. 15. Locations of the recording electrodes. The grid represents 1 mm<sup>2</sup>. The locations were determined by relative distances from the bregma. "A-F" are the recording electrodes. The skull image is taken from [2]

A rat experiment was used to confirm that the epidural electrode was available for motion classification. A 14-week-old SD rat weighing 455 g was used. We simultaneously measured both epidural potentials at six electrodes (Fig. 15) and paws motions by monochrome video camera during exploratory locomotion in an open-field cage (450 mm square) provided constant white noise. The epidural potentials was amplified with a gain of 5000–10000 and recorded at a sampling rate of 20 kHz. The digitalization was 12-bit in  $\pm 10$  V. The frame rate of video recording was approximately 30 frames per second. The video data were used to confirm the rat motions in offline analysis. To investigate the relationship between the recorded signals and the motions, the signals were classified into the motions and the accuracy of the classification was calculated. We selected objective motions: the state of stop, right forefoot lifting, left forefoot lifting, both forefeet lifting, and rest in the cage.

The analytical process was conducted in three steps consisting of a difference calculation, a feature extraction, and a classification. First, the signals recorded by the six electrodes were used to calculate the difference between each electrode to remove in-phase noise. Fifteen differential signals were calculated from the six electrodes. Because epidural electrodes cannot detect neural firing spikes, power spectra

were used as features. Neuron groups that have different functions are thought to be activated at different frequencies. A short-time Fourier transform was employed as the feature extraction method. In this condition, the frequency resolution is constrained to be approximately 20 Hz. A feature vector was made of the 360 power spectra that consist of 24 frequency bands of 0–500 Hz per differential signal (The 40–60 Hz spectrum was removed to prevent hum noise of 50 Hz). We used nonlinear SVM as the classification method. The feature vectors were labeled with the states of motion using video data, and divided into learning data and test data. A classification test was conducted by five-fold cross validation. Groups of motions were set up to classify them at one time. The groups had 2–4 motions and each group was classified separately by SVM.

## Results and Discussions

Fig.16 shows time-line epidural signals that were measured during the motion change from stop to lifting both forefeet. Fig.16 a) shows the differential potential between the electrodes A and E, and b,c) shows the power spectra of the differential signals. Fig.16 d) shows the video data, and roman numerals of the pictures mean the time-line in a) and b). Fig.16 indicates the epidural signal changes with the rat’s motion.

Table 1 shows the accuracies in the classification using a 360–dimension feature vector. In the section of “Motion,” RF, LF, and BF mean right forefoot lifting, left forefoot lifting, and both forefeet lifting, respectively. It is important to acquire temporally-stable signals, and we calculated the accuracies in each number of days from fifth to thirteenth days after surgery. The accuracies varied with the objective motions: from 50 to 100 % in two-motion classification, and from 65 to 75 % in three- and four-motion classifications. The difference of the accuracy among four days is almost less than 10 %. This results show that it is possible to measure temporally-stable signals and get stable accuracy in the classification with the proposed method approximately during ten days after surgery.

Next, we investigated that the accuracy was changed or not depend on the electrode location. According to the results, the accuracies of the motion were various with electrode locations (data not shown). Suitable electrode location was different in objective motions, and also this suitable location was temporally changed. These results indicate that recording broad area of brain is needed in many-motion classification, because the activated area is different in different motions and signal characteristics of the electrode may be time varying.

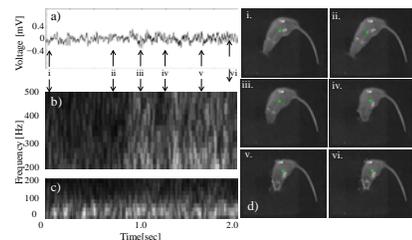


Fig. 16. Sample of the measured data. a)Differential potential between electrodes A and E during 2.0 seconds. b,c)Power spectra of a). Z scale is different

between b) and c). d)Pictures of the rat recorded below the cage. Roman numbers at the upper left of the pictures indicate a time-line marked between a) and b). The rat set forefeet on ground during i–iii, and lifted them during iv–vi.

Table 2. Classification results of the motions. In the Motion section, RF, LF, and BF mean right forefoot lifting, left forefoot lifting, and both forefeet lifting, respectively.

Num. of motions	Combination of motions	Accuracy [%]			
		Day 5	Day 6	Day 7	Day 13
Two	Stop- BFF	75.8	85.6	83.2	—
	Stop-RFF	89.0	87.1	80.2	81.1
	Stop-LFF	80.5	85.2	87.4	65.0
	Stop-Rest	96.1	89.7	98.6	97.3
	RFF-LFF	46.5	55.5	38.6	50.0
	RFF-BFF	70.8	68.0	77.1	—
Three	Stop-RFF-BFF	66.3	65.7	72.6	—
Four	Stop-RFF-BFF-Rest	73.2	71.2	77.3	—

## V. CONCLUSIONS

For the purposes of development of a method for motor paralysis of the legs, we produced a biofeedback system that helps for walking by using electrical stimulation for reflex muscular contraction. As a result, to clarify the modalities for the location of the lower leg muscle activity to electrical stimulation, stimulus-response map obtained. Using this stimulus-response map, standing work, confirmed the possibility of walking aids for motor function. Meanwhile, motion estimation method is proposed by using a rat animal from epidural measurement signal. A classification algorithm based on SVM obtained 70% accuracy of discrimination of four motions for 10 days. Four motion includes stop, lift the two front legs, lift the right anterior leg, and resting state.

## REFERENCES

- [1] Alejandro Hernandez Arieta, Kato Ryu, Hiroshi Yokoi, Takashi Ohnishi, and Tamio Arai An fMRI Study on the Effects of Electrical Stimulation as Biofeedback. Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 1-4244-0259-X/06/\$20.00 ©2006 IEEE, pp 4336-4342, (2006)
- [2] George Paxinos and Charles Watson, *The rat brain in stereotaxic coordinates*, Sydney: Academic Press, 1998.
- [3] Takeshi Uejima, Kahori Kita, Toshiyuki Fujii, Ryu Kato, Masatoshi Takita, Hiroshi Yokoi, Motion Classification using Epidural Electrodes for Low-Invasive Brain-Machine Interface, 31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC2009), pp. 6469-6472, (2009)
- [4] Takeshi Uejima, Toshiyuki Fujii, Ryu Kato, Masatoshi Takita, Hiroshi Yokoi, A Study on Motion Estimation using Epidural Electrodes of Rat Brain, Journal of the Robotics Society of Japan, Vol.27, No.7, pp. 30-36, (2009) in Japanese.

# Study on brain adaptation using rat-machine fusion systems and multi functional neural electrodes

Takafumi Suzuki\*, Kunihiko Mabuchi\*

**Abstract—** The goal of our research project is to elucidate the brain adaptation function using rat-machine fusion systems and multi functional neural electrodes. To achieve this goal, we have developed fundamental techniques. These techniques include A) automatic adaptation of vehicle controller to time-varying neural signals recorded in these rat-machine fusion systems, and B) elemental techniques about flexible neural probes with micro fluidic channels for injection (or measurement) of medicines.

## I. INTRODUCTION

The goal of our research project is to elucidate the ability of the brain (especially the motor center) to adapt to a variable body environment by using a rat-machine fusion system in which the body's environmental conditions are changeable and also by using multi functional neural electrodes. We plan to construct a "rat car" vehicle system in which the car is controlled by neural signals in the motor cortices of rats. The system allows us to change the relationship between the motor command signals and the effectors (the muscles or the vehicle) arbitrarily. By using multi-channel recordings of neural signals together with injection and recording of certain medicines into the system, we plan to elucidate the brain property mentioned above.

We have been engaged in developing fundamental techniques to achieve this goal. The techniques includes A) automatic adaptation of vehicle controller to time-varying neural signals recorded in these rat-machine fusion systems, and B) elemental techniques for long-term stable neural recording using devices such as flexible neural probes with micro fluidic channels for injection (or measurement) of medicines or with a sensor for glutamate detection.

## II. RESULTS

### A) RatCar system[1, 4, 5]

#### A-I) Introduction

In this section, the outline of the "RatCar system" will be explained, and then the introduction and the potential of automatic adaptation of vehicle controller to time-varying neural signals will be shown.

We have developed a rat-machine fusion system in the form of a small vehicle BMI system, which we call the 'RatCar'. A unique point of our RatCar system is that a neural signal source (i.e., a rat) is mounted on the vehicle body and the two

components move around as a unit. The rat is therefore provided with somatosensory feedback as the vehicle moves. This enables the rat to realize that its desire to move has been satisfied through the vehicle movement. We expect this condition to increase the ability of the rat to adapt to the system. Our ultimate goal is to illude the rat into recognizing the vehicle as corresponding to its own original limbs, and this will enable use of the RatCar as a platform for future neuroscience research. In addition, the movement of the vehicle system causes electromagnetic noise and artifacts in the recorded signals, an inevitable problem for real applications in hospitals and day to day society. The development of the RatCar system will help us investigate and solve these problems.

Although a simple linear model that we proposed in our former report[1] estimated an abstract locomotion velocity of a rat according to its neural firing rates, the results with too rough fluctuations were not suitable to control the RatCar vehicle. The model was divided into two sections; a section to correlate rat's locomotion velocity with each neural firing and another to estimate locomotion velocity compiling the whole pattern of neural firings. It enabled stable control of the vehicle even though the model precision had been inadequate. In addition, changing states both in the brain and the machine were observed through the model parameters.

#### A-II) Methods

First, tungsten wire electrodes (40  $\mu\text{m}$  in diameter) coated with Parylene-C polymer (5  $\mu\text{m}$  thick) were implanted in the motor cortex and basal ganglia regions which were determined according to a stereotaxic atlas of the rat brain(Table 1)[3].

As the rat ran inside the wheel-formed device, those electrodes transmitted neural spikes to the outside of the body followed by amplifier (5,000 times) and band-pass filter (300 Hz - 5 kHz).

Table 1 Electrodes coordinate (to *bregma*)

region	anterior [mm]	lateral [mm]	ventral [mm]
M1	-0.7	2.5	1.6
STR	0.5	3.0	4.0
GP	-0.7	3.4	6.0
STN	-3.5	2.6	7.3

(Negative values in anterior represents posterior distance.)

Those spikes were then sampled (25 kHz) and sorted to calculate firing rates  $s(t) = (s_1(t) \dots s_n(t))$  in every 100 ms bin

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for each neuron. Finally, the principal component analysis normalized and whitened variances of those firing rates.

$$\mathbf{y}(t) = RL^{1/2}(\mathbf{s}(t) - \boldsymbol{\mu}) \quad (1)$$

$$\boldsymbol{\mu} = E\{\mathbf{s}(t)\} \quad (2)$$

$$E\left\{(\mathbf{s}(t) - \boldsymbol{\mu})(\mathbf{s}(t) - \boldsymbol{\mu})^T\right\} = RLR^T \quad (3)$$

( $L$  : diagonal)

Meanwhile, the actual locomotion velocity  $v(t)$  recorded as a rotating speed of the wheel was applied to identify or evaluate the model.

Our model to estimate locomotion velocity of a rat has a state space representation described as,

$$\mathbf{x}(t+1) = F\mathbf{x}(t) + G\xi(t) \quad (4)$$

$$\mathbf{y}(t) - \sum_{i=1}^p a_{n,i}\mathbf{y}(t-i) = H\mathbf{x}(t) + \boldsymbol{\eta}(t), \quad (5)$$

where

$$\mathbf{x}(t) \equiv \begin{pmatrix} v(t) \\ (v(t) - v(t-1))/\Delta t \\ (v(t) - 2v(t-1) + v(t-2))/\Delta t^2 \end{pmatrix}$$

$$F \equiv \begin{pmatrix} 1 & \Delta t & 0 \\ 0 & 1 & \Delta t \\ 0 & 0 & 0 \end{pmatrix}$$

$$G \equiv I$$

$$\Delta t = 100\text{ms (bin size)}$$

$$\boldsymbol{\xi} : \text{model transition error (initially } \mathbf{0}\text{)}$$

$$\boldsymbol{\eta} : \text{model output error (initially } \mathbf{0}\text{)}$$

In the algorithm, the equation (4) describes an update of internal states consist of the rat's locomotion velocity and its periodic differences. Meanwhile, the equation (5) correlates a combination of neural firings to the locomotion velocity with an output matrix  $H$ . Note that the neural firings were given as residuals of an auto-regression process (defined by parameters  $a_{n,i}$ ) applied to neural firing rates.

To solve the model (i.e., to acquire  $v(t)$ ,  $H$ ,  $a_{n,i}$ ), two sections were applied as follows. First,  $H = (h_1, \dots, h_n)$  and  $a_{n,i}$  were identified by another state space representation for each neuron as actual locomotion velocity array  $x(t)$  was given:

$$\mathbf{u}_n(t+1) = \mathbf{u}_n(t) \quad (6)$$

$$\mathbf{y}_n(t) = (\mathbf{h}_n \ a_{n,1} \ \dots \ a_{n,p}) \mathbf{u}(t), \quad (7)$$

where

$$\mathbf{u}_n(t) \equiv (\mathbf{x}(t) \ y_n(t-1) \ \dots \ y_n(t-p))^T.$$

The measurement update algorithm from Kalman filter[2] were applied to identify  $\mathbf{u}_n(t)$  and therefore  $a_{n,i}$  and  $h_n$ .

Kalman filter algorithms (the time update and the measurement update) were then applied to the former state space model (4,5) to estimate locomotion velocity  $v(t)$ . Note that the algorithms were able to continue the estimation of the locomotion velocity  $v(t)$  as the parameters  $a_{n,i}$  and  $H$  were updated.

Six male Wistar rats were used as subjects. They were trained to walk inside the wheel-formed device described above after two days after the implant surgery. Although they had electrodes implanted both in motor cortex and basal ganglia, we focused only on the motor cortex in this experiment. The recording trials were divided into approximately 1 minute periods to prevent a rat from getting tangled in recording cables. While the first trial was used to identify the model and to observe varying parameters, the rest trials (typically 2; 120 s) evaluated a precision of the model.

### A-III) Result

The result of an open estimation shows that rats D, E and F gave a high correlation over 0.2, although these trials contained other movements unrelated to locomotion.

More detailed estimation for rat E, which had a highest correlation, showed that while estimated value by our presented algorithm well followed start, stop and drastic changes of actual locomotion, it tended to be 3 - 4 times larger in amplitude. As a whole for rat C, however, the estimated velocity often failed to follow the actual one which resulted in the low correlation.

### A-IV) Discussion and Conclusion

The results showed that the first 10 - 15 seconds period of the identification trial converged the initial covariance components to achieve a basic estimation of locomotion velocity. As long as these values stayed constant, the model well estimated locomotion velocity especially for drastic changes. On the other hand, some of them gradually changed after the initial identification period had passed in the case of rat C, some, which resulted in a weaker correlation with velocity.

These changes were caused either by plasticity of the brain, modification in recording condition, or dynamics in brain activity that our model did not take into account. It is not able to clearly distinguish them with our methods by themselves since our current results show phenomenological correlations between each neural firing and the locomotion velocity. Our results, however, still suggest that those changes were caused by some sort of state transition in the brain.

For future studies, continuous recording for long hours with a rat mounted on the vehicle will suggest quantitative results on dynamical changes and plasticity of the brain as connected to BMI system.

We also investigated the conditions inducing synaptic changes through intracortical microstimulation synchronized with lever push movement in the rat[6]. Invasive brain-machine interface approaches are generally based on the process containing acquiring neural signals by implanted electrodes, estimating movement intention by using these signals and controlling an artificial device. In this process, we couldn't always record neural signals from all of the electrodes inserted, even though it is expected to acquire as many signals as possible to estimate more precisely. To avoid

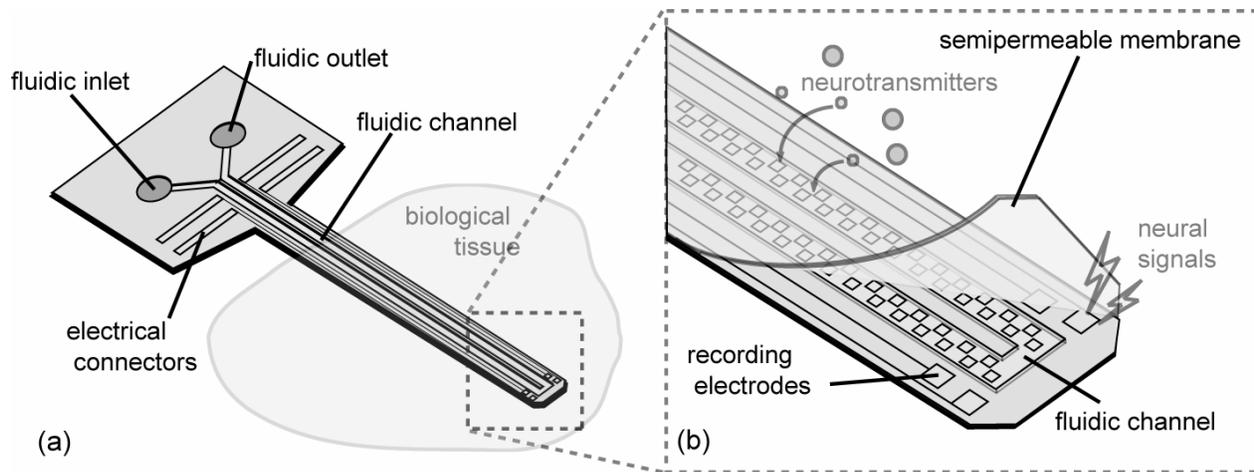


Fig. 1. Conceptual illustration of a probe. (a) Overview image of the probe. The probe is inserted into biological tissue. (b) Tip of the probe with recording electrodes and a fluidic channel. The fluidic channel is covered with a semipermeable membrane. When the probe is inserted into the brain, the microelectrodes record neural signals, and the fluidic channel collects neurotransmitter from the extracellular fluids around the point of interest.[7]

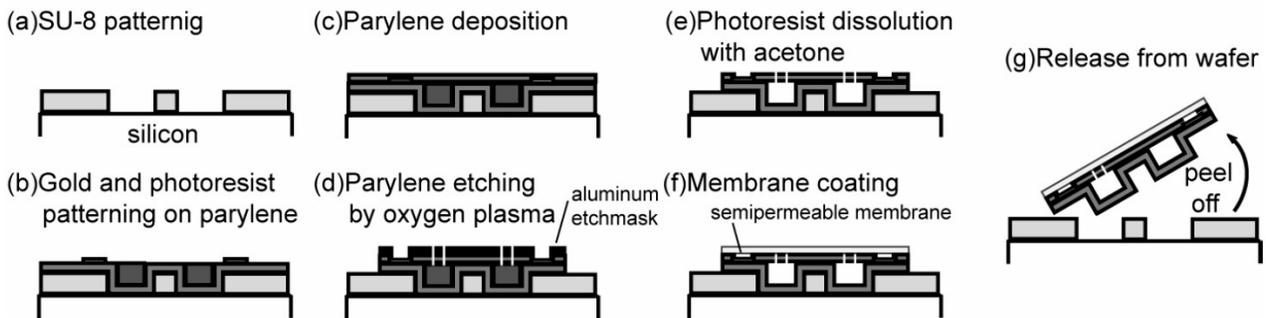


Fig. 2 Fabrication process of the probe[7]

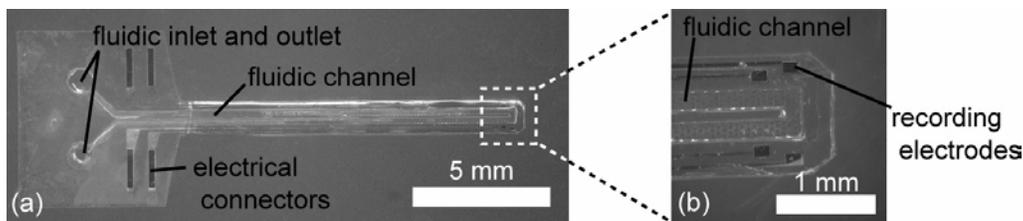


Fig. 3 The probe was fabricated on a 25- $\mu$ m-thick Parylene C substrate. (b) The fluidic channel is U-shaped at the tip of the probe. [7]

causing extra damage to the brain by useless electrodes, we examined whether induction of synaptic changes artificially occurred in the rat motor cortex through intracortical microstimulation.

## B) Multi-functional neural electrode

### B-I) Introduction

In this section, flexible probes to record both neuroelectrical and neurochemical activities are shown as an example of the multi-functional neural electrodes we have developed[6]. The fabrication process is based on the method

we have reported previously[8]

### B-II) Methods

Figure 2 shows the fabrication process of the probe. First, an SU-8 mold (50  $\mu$ m thick) was made on a silicon wafer. Then, a 30-40  $\mu$ m thick photoresist layer and a patterned gold layer were sandwiched between two Parylene thin films (the first layer is 15  $\mu$ m in thickness; the covering layer is 10  $\mu$ m in thickness) on the mold. The photoresist was used as a sacrificial layer to form the fluidic channel. After oxygen plasma etching with an aluminum layer as an etchmask, which

defined the shape of the probe and the opening sections of the fluidic channel, the fluidic channel was opened by dissolution of the photoresist in an acetone bath. A semi-permeable membrane was prepared by spincoating an acetone solution containing cellulose acetate and formamide. The membrane was then transferred onto another wafer with the neural probe, and was fixed to the probe by drying acetone. Finally, the structure was peeled off from the SU-8 mold.

### B-III) Results and Discussion

The whole structure of the probe is shown in Figure 3a. The size of the probe is 1.2 mm in width, and 12 mm in length (excluding the connecting site). These probes have four microelectrodes for neural recording and a fluidic channel covered with a semi-permeable membrane; the membrane is used for microdialysis in the brain (Figure 3b). The size of the fluidic channel was 170  $\mu\text{m}$  in width, and 30-40  $\mu\text{m}$  in height. As a result of an in vitro perfusion test, no leakage of dialysate was observed from the fluidic channel. The measured impedance of the gold electrodes ( $100 \times \mu\text{m}^2$ ) was approximately 600k $\Omega$  at a frequency of 1 kHz.

### III. CONCLUSION

We report the results of this project such as A) automatic adaptation of vehicle controller to time-varying neural signals recorded in these rat-machine fusion systems, and B) elemental techniques about flexible neural probes with micro fluidic channels for injection (or measurement) of medicines or with a sensor for glutamate detection.

### REFERENCES

- [1] Osamu Fukayama, Noriyuki Taniguchi, Takafumi Suzuki, Kunihiko Mabuchi, Control of a vehicle-formed BMI system for rats by neural signals recorded in the motor cortex, Proceedings of the 3rd International IEEE EMBS Conference on Neural Engineering, 2007, pp. 394 - 397.
- [2] R. E. Kalman and R. S. Bucy, New Results in Linear Filtering and Prediction Theory, Trans. ASME, J. Basic Eng., Vol. 83D, No. 1, 1961, pp. 95 - 108.
- [3] G. Paxinos and C. Watson, The Rat Brain in Stereotaxic Coordinates, Compact Third Edition, 1997, Academic Press.
- [4] Osamu Fukayama, Noriyuki Taniguchi, Takafumi Suzuki, Kunihiko Mabuchi: Automatic Adaptation of Vehicle Controller to Time-Varying Neural Signals Recorded in RatCar System; A Vehicle-formed BMI, Proc. of Joint 4th International Conference on Soft Computing and Intelligent Systems and 9th International Symposium on Advanced Intelligent Systems, pp. 253-256 (2008)
- [5] Osamu Fukayama, Noriyuki Taniguchi, Takafumi Suzuki, Kunihiko Mabuchi: RatCar system for estimating locomotion states using neural signals with parameter monitoring: Vehicle-formed brain-machine interfaces for rat, Proceedings of the 30th Annual International Conference of the IEEE EMBS, pp. 5322-5325 (2008)
- [6] Takuya Kohama, Osamu Fukayama, Takafumi Suzuki, Kunihiko Mabuchi, Induction of Synaptic Changes in the Rat Primary Motor Cortex through Electrical Stimulation synchronized with Lever Control, Proceedings of the 24th SICE Symposium on Biological and Physiological Engineering, pp. 47-48 (2009) (in Japanese).
- [7] Naoki Kotake, Takafumi Suzuki, Kunihiko Mabuchi, Shoji Takeuchi: A flexible Parylene neural probe combined with a microdialysis membrane, Proc. of microTAS 2008, pp. 1687-1689 (2008).
- [8] Shoji Takeuchi, Dominic Ziegler, Yumi Yoshida, Kunihiko Mabuchi, Takafumi Suzuki, Parylene flexible neural probe with micro fluidic channel, Lab on a chip, Vol. 5, pp. 519-523 (2005).

# Analysis of relation between neuronal coding and body movement using BMI

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**Abstract** — The present study is analyzing how body movement is involved in neuronal coding (representation) using multineuronal recording and a brain-machine interface (BMI). In 4 years of research project, we have developed an experiment system with a new and high-performance BMI. We report that neuronal firing frequencies of neuronal population remarkably changed when they were working, via BMI, as neuronal codes instead of behavior to get reward. Firing synchrony also changed especially in the hippocampus. Consequently, our research suggests that the brain can highly change its firing frequency and synchrony when it removes the restraint of body by BMI.

## I. INTRODUCTION

Recognition and detection of valid information in the environments are must for animals to behave adaptively, that necessarily require neural coding in the brain. Recent neuroscience studies have suggested that neural coding is based on activity of functional groups of neurons, i. e., cell assembly (Fig. 1), as the famous psychologist D.O.Hebb suggested. However, as the other famous psychologist J.J.Gibson indicated, recognition and detection of valid information need action to and interaction with the environments of much information. This suggests that real features of neuronal coding could be experimentally uncovered by investigating how body movements are involved in neural activity of coding in the working brains.

## II. PURPOSE

The aim of the present study was developing high-performance BMI system and then showing how body movements affect and restrict neural coding in the brain. For that, we compared multi-neuronal activity when the rat was performing a simple operant task by its behavior and by its neuronal activity via BMI. The target brain regions were the hippocampus and the neocortex. We finally suggest what the role of body movement was for neuronal coding in the brain.

## III. ORIGINALITY

The present study rejects the classical neuroscience framework, i.e., recognizing the brain as a simple device which passively perceives and processes incoming information in the environments. Instead, we focus on interactions between neural coding and body movements and aim to experimentally investigate them. To establish the BMI system for the present study, developing and integrating new hardwires and software and collaboration between psychological behavior experiments and neurophysiological recording experiments are required. That is surely a new multidisciplinary project among different fields of science.

## IV. RESULT 1 (Original Methods)

We have constructed a novel BMI consisting of automatic and real-time spike sorting system with independent component analysis (RASICA, Real-time and Automatic Sorting with Independent Component Analysis) in combination with a newly developed multi-electrodes (dodecatrode) for long-term recording from multi-sites of the brain (Fig.1).

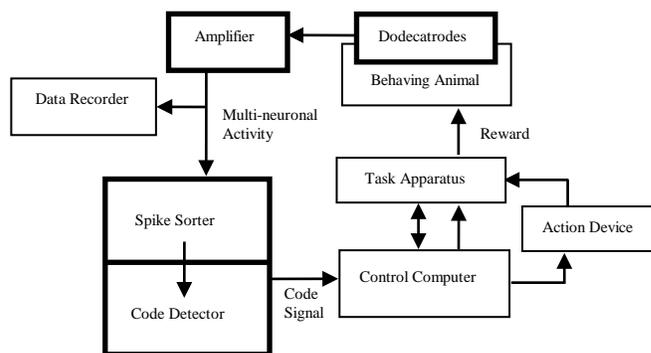


Fig. 1: A schematic diagram of the BMI system. Thick lines are implicated in the RASICA.

We have then developed a specific method of surgery with PC micro screws implanted in the skull surfaces of rats (Fig. 2). This method guarantees stable recording of multi-neuronal activity for longer periods, i.e., more than half a year.



Fig.2: PC micro screws implanted in the skull surface by surgery. The PC screw has diameter of 1.5 mm and implanted into a hole tapped in the skull. Then microdrives with electrodes are fixed with dental cement.

The main task was a simple free response task (Fig.3). When the rat used its body movement, it poked the nose to a hole (nose-poke behavior) to get reward of pellet. When the rat used its neuronal activity via BMI, a transparent panel was set just in front of the hole and some specific multi-neuronal activity instead of behavior could deliver the reward.

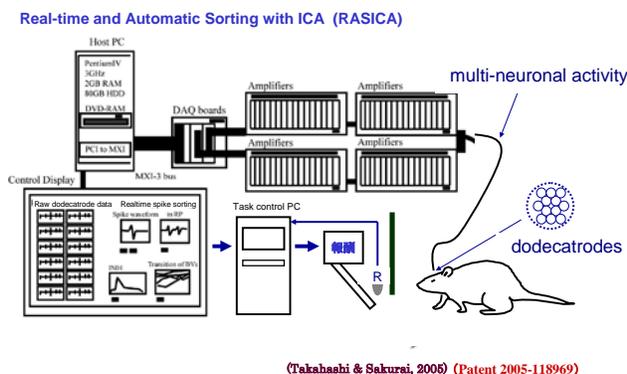


Fig. 3 : BMI system for the free response task. It consists of multi-neuronal recording from the dodecatrodes and real-time spike sorting with ICA (RASICA).

We also have developed a target-approach task and a target-operation task with BMI (Figs. 4 and 5). In the former task, the rats moved to the wall in the opposite side of the box to do nose-poke behavior to get reward. In the latter task, multi-neuronal activity connected to the BMI made the wall move to the rats for its nose-poke behavior.

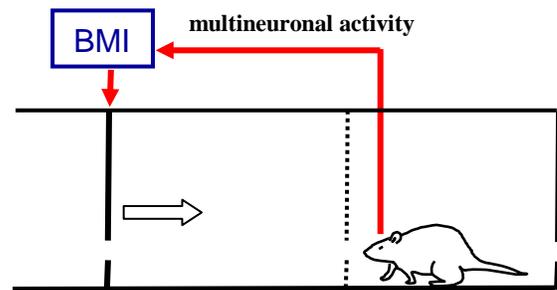


Fig.4: Schematic drawing of the target-operation task. The target (the hole on the left wall) is being operated to approach to the rat by neuronal codes.

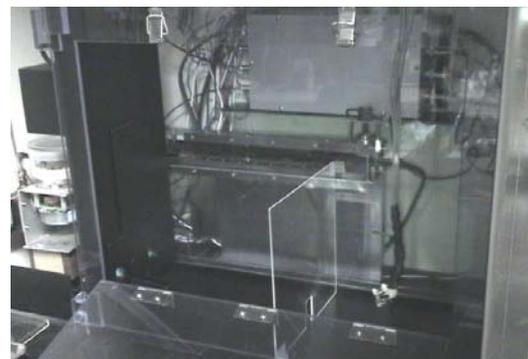


Fig. 5: The apparatus for the target-operation task. The black wall on the left side moves to the right side with the pellet dispenser.

We can use various specific patterns of neuronal activity to control the pellet dispenser instead of behavior and call it “neuronal code”. The neuronal code is firing frequency or synchrony of neurons, which can be selected from any of the recorded neurons. When the RASICA system detects specific neuronal codes, it transmits signals to a computer that controls the behavioral tasks and the reward dispenser. Then the specific neuronal codes effect the behavioral tasks and deliver the reward instead of the animal’s behavior. Figure 6 is a schematic drawings of detection of the neuronal codes. Even

when the plural neurons fire synchronously and an overlapped waveform is recorded by the dodecatrode, the system automatically separates it to neuronal spikes from the individual neurons by ICA. Fig. 7 is the computer displays of the BMI system.

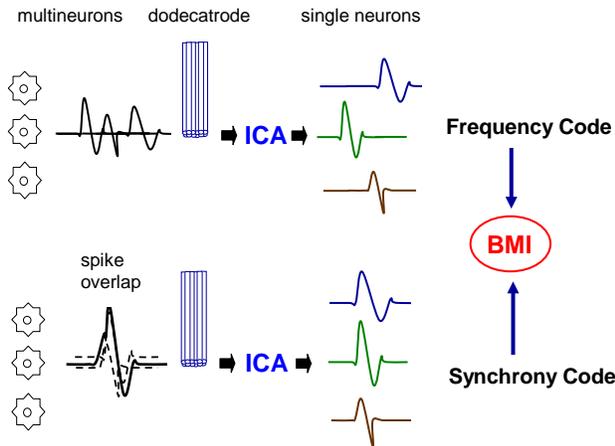


Fig. 6: Two types of neuronal codes detected by RASICA. Upper panel, neuronal code of spike frequency of the neurons. Lower panel, neuronal code of spike synchrony of the neurons.

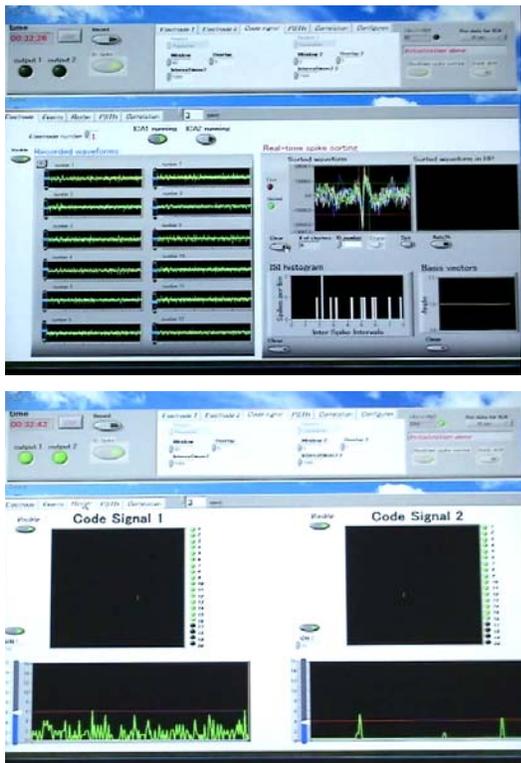


Fig. 7: Computer displays of the BMI system with RASICA. Upper display, Neuronal spikes on 12 microwires of the dodecatrode (left) and waveforms of separated individual neurons (right). Lower display, Firing frequency (left low) and synchrony (right low) of the separated 16 neurons

## V. RESULTS 2 (Neuronal Activity Changes)

We have shown clear dynamic changes of neuronal activity in the free-response task when it functioned as neuronal codes instead of behavior. In the first day, nose-poke behavior caused delivery of a food pellet. In the second and third days, multineuronal activity was recorded from the neocortex (somatosensory) and hippocampal CA1. The neuronal codes that deputized for the nose-poke behavior were higher spike frequency (frequency code) in the second day and occurrence of spike synchrony (synchrony code) in the third day. Fig. 8 shows mean numbers of rewards delivered as a result of the nose-poke behavior and the neuronal codes in the free response task. In the first day (behavioral task), the rats obtained the reward constantly during the 30 min session. In the 2nd day (frequency code), the rats soon learned to frequently generate the neuronal code and obtained more rewards than in the previous day. In the 3rd day (synchrony code), the rats could not increase the synchrony code.

Rats = 3, Electrode sites = 3 (each has 5-8 multiple neurons), Region = NCx

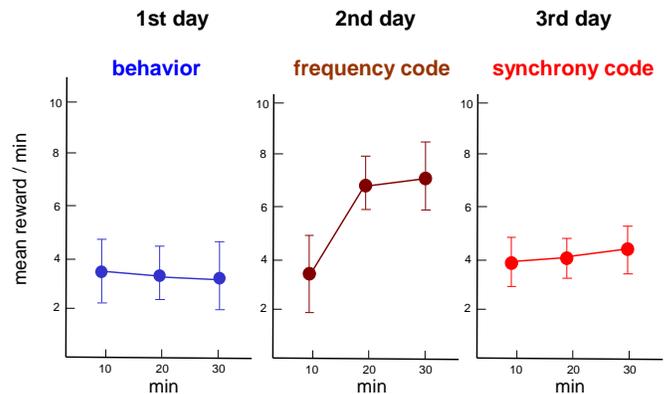


Fig. 8: Mean numbers of rewards delivered by behavior (1st day) and neuronal codes (2nd and 3rd days) in the free-response task. The data were obtained from 3 dodecatrodes implanted in the neocortices of 3 rats.

The data in Fig. 9 were obtained from the dodecatrodes implanted in hippocampal CA1. The frequency code in the second day rapidly increased (Fig. 8). In the third day, the synchrony code showed an increment and the rats obtained more reward than by performing the behavior.

## MAJOR REFERENCES

Rats = 4, Electrode sites = 4 (each has 6-10 multiple neurons), Region = HPC

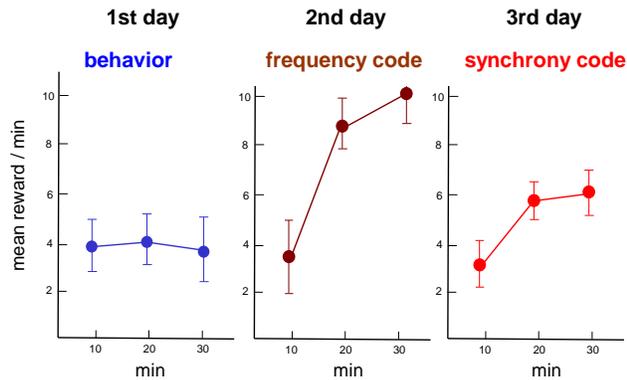


Fig. 9. Mean numbers of rewards delivered by behavior (1st day) and neuronal codes (2nd and 3rd days) in the free-response task. The data were obtained from 4 dodecatrodes implanted in hippocampal CA1 of 4 rats.

We analyzed activity changes of hippocampal CA1 neurons when the rat was performing the target-approach task and target-operation task. Fig. 10 is data to the present showing increment of firing frequencies of the neurons in the second day of training of the target-operation task..

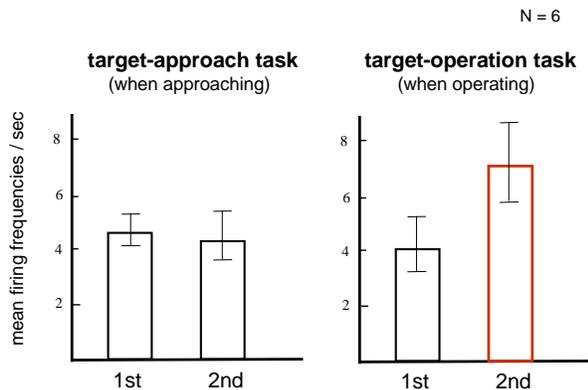


Fig. 9: Mean firing frequencies of the hippocampal CA1 neurons during the 2 days of training of the target-approach task and target-operation task.

## ACKNOWLEDGEMENTS

The author thanks Dr. Susumu Takahashi (Kyoto Sangyo University), Dr. Toshio Aoyagi (Kyoto University) and Dr. Masaki Nomura (Kyoto University) for their collaborating.

- (1) Sakurai, Y., Takahashi, S. and Nomura, M. (2009) Dynamic changes of firing frequency and synchrony of the rat hippocampal neurons caused by BMI. *Proceedings of 3rd International Symposium on Mobiligence*, 206-210.
- (2) Choi, K., Hirose, H., Sakurai, Y., Iijima, T. and Koike, Y. (2009) Prediction of arm trajectory from the neural activity of the primary motor cortex with modular connectionist architecture. *Neural Networks*, 22, 1214-1223.
- (3) Takahashi, S. and Sakurai, Y. (2009) Information in small neuronal ensemble activity in the hippocampal CA1 during delayed non-matching to sample performance in rats. *BMC Neuroscience*, 10, 115:1-11.
- (4) Takahashi, S. and Sakurai, Y. (2009) Sub-millisecond firing synchrony of closely neighboring pyramidal neurons in hippocampal CA1 of rats during delayed non-matching to sample task. *Frontiers in Neural Circuits*, 3, 9:1-18.
- (5) Sakurai, Y. (2009) Plastic reorganization of neuronal networks caused by brain-machine interfaces. *Brain* 21, 12, 42-47 (In Japanese)
- (6) Sakurai, Y. (2009) Connecting the brain with machines - what the brain-machine interfaces will realize. *Kagaku*, 79, 535-537 (In Japanese).
- (7) Takahashi, M., Lauwereyns, J., Sakurai, Y. and Tsukada, M. (2009) A code for spatial alternation during fixation in rat hippocampal CA1 neurons. *Journal of Neurophysiology*, 102, 556-567.
- (8) Sakurai, Y. and Takahashi, S. (2008) Dynamic synchrony of local cell assembly. *Reviews in the Neurosciences*, 19, 425-440.
- (9) Sakurai, Y. (2008) Present states and future problems of invasive BMI. *Journal of the Japan Society of Mechanical Engineers*, 111, 916-919 (In Japanese).
- (10) Takahashi, S. and Sakurai, Y. (2007) Coding of spatial information by soma and dendrite of pyramidal cells in the hippocampal CA1 of behaving rats. *European Journal of Neuroscience*, 26, 2033-2045.
- (11) Nomura, M., Sakurai, Y. and Aoyagi, T. (2007) Analysis of multineuron activity using the kernel method. *Journal of Robotics and Mechatronics*, 19, 364-368.
- (12) Sakurai, Y. (2007) The present and future of brain-machine interfaces. *System, Control, and Information*, 51, 464-472. (In Japanese)
- (13) Sakurai, Y., and Takahashi, S. (2006) Dynamic synchrony of firing in the monkey prefrontal cortex during working memory tasks. *Journal of Neuroscience*, 26, 10141-10153.

# Exploring reinforcement learning and motivation

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**Abstract** We addressed the role of neuronal activity in the pathways of the brainstem-midbrain circuit in reward and the basis for believing that this circuit provides advantages over previous reinforcement learning theory. Several lines of evidence support the reward based learning theory proposing that midbrain dopamine (DA) neurons send a teaching signal (the reward prediction error signal) to control synaptic plasticity of the projection area. However, the underlying mechanism of where and how the reward prediction error signal is computed still remains unclear. Since the cholinergic pedunculopontine tegmental nucleus (PPTN) in the brainstem is one of the strongest excitatory input sources to DA neurons, we hypothesized that the PPTN may play an important role in activating DA neurons and reinforcement learning by relaying necessary signals for reward prediction error computation to DA neurons. Recently, to elucidate the functional role of the PPTN in reward-seeking behavior, we recorded single PPTN neurons during a reward valued-conditioned saccade task and found that two distinct groups of neurons signal predicted and actual reward values, both of which are necessary for the computation of reward prediction error as represented by DA neurons.

## I. Introduction

The cholinergic system is one of the most important modulatory neurotransmitter systems in the brain, and controls neuronal activity that depends on selective attention, and anatomical and physiological evidence supports the idea of a 'cholinergic component' of conscious awareness. The PPTN in the brainstem containing both cholinergic and non-cholinergic neurons and the PPTN is one of the major sources of cholinergic projections in the brainstem. In the older literature, the PPTN is thought to be the central part of the reticular activating system, which provides background excitation for several sensory and motor systems essential for automatic control of movement, perception and cognitive processes. It has long been known that the PPTN is a crucial element in the regulation of the rhythms in the

cortex that are associated with wakefulness and REM sleep.

Anatomically, the PPTN has reciprocal connections with the basal ganglia: the subthalamic nucleus (STN), the globus pallidus, and the substantia nigra, and recently, PPTN has been as argued to form a part of the basal ganglia. Further, the PPTN also has reciprocal connections with catecholaminergic systems in the brainstem: the locus coeruleus (LC; noradrenergic) and the dorsal raphe nucleus (DRN; serotonergic). This basal ganglia-PPTN-catecholaminergic complex has been proposed to play an important role in gating movement, controlling several forms of attentional behavior and reinforcement process. Despite these abundant anatomical findings, however, the functional importance of the PPTN is not yet fully understood.

Numbers of lesion and drug administration studies using rodents have indicated that the PPTN is involved in various reinforcement processes. According to a physiological study in cats, the PPTN is thought to relay either a reward signal or a salient event in a fully conditioned situation. Anatomically, the PPTN receives reward input from the lateral hypothalamus and the limbic cortex. Conversely, the PPTN abundantly projects to midbrain DA neurons of the substantia nigra pars compacta (SNc) and ventral tegmental area (VTA), which encode a reward prediction error signal for reinforcement learning.

Reinforcement learning has been one of the central topics in a broad range of scientific fields for the last two decades. It is expected to provide a systematic understanding of adaptive behaviors, including simple classical and operant conditioning of animals as well as complex social and economical human behaviors that maximize behavioral benefits; and is also useful in machine learning and robotics.

The basic process of reinforcement learning involves choosing a behavior for which the maximal reward is predicted and revising this prediction to minimize the reward prediction error, the difference between the predicted and actual reward. The essence of this theory is that the

behaviors are optimized by choosing the one for which the maximal reward is predicted, and that the reward prediction is revised so as to minimize the reward prediction error, the difference of the predicted and actual reward of the behaviors.

Recent neurophysiological studies have shown that midbrain DA neurons encode the reward prediction error signal and that the striatum and cerebral cortices use this signal to perform reinforcement learning with dopamine-induced synaptic plasticity. Thus, computing the reward prediction error is one of the most essential issues of reinforcement learning, however the most essential question of which neural structures provide the signals for computation of the reward prediction error by the midbrain DA neurons remains elusive.

For DA neurons, the PPTN is one of the strongest excitatory input sources. For the excitatory inputs, the PPTN neurons release glutamate and acetylcholine to target neurons, and the glutamatergic and cholinergic inputs from the PPTN make synaptic connections with DA neurons, the cholinergic modulation of the DA-containing neurons in the midbrain is excitatory, and electrical stimulation of the PPTN induces a time-locked burst in DA neurons in the rat. Consistently, chemical or electrical stimulation of the PPT increases DA release in the striatum. The other electrophysiological experiments have shown that acetylcholine (ACh) acts through both nicotinic (nAChRs) and muscarinic (mAChRs) receptors to depolarize DA neurons and to alter their firing pattern. Thus, PPTN activity and ACh provided by the PPTN can facilitate the DA neuron's burst firing and appear to do so via mAChRs and nAChR receptor activation. In addition, some of the effects induced by PPTN stimulation can be blocked by mAChR agonist carbachol into the PPTN. This finding is consistent with the fact that cholinergic neurons in the PPTN express the inhibitory muscarinic autoreceptors and suggests that activation of these receptors inhibits cholinergic inputs to the DA neurons.

Furthermore, midbrain DA neurons are dysfunctional following excitotoxic lesioning of the PPTN. A number of studies have found impairments in learning following excitotoxic lesions of the PPTN. Thus, the abundant anatomical, electrophysiological and pharmacological studies of slice and whole animal preparations indicate that the PPTN receives signals from the reward related structures including the cerebral cortices and the striatum and provides strong excitatory inputs to the DA neurons. Interestingly, the DA/ACh interaction

seems to be mutual; the SNc projects back to PPTN neurons, affecting their excitability. Even though the dopaminergic input to the PPTN is low compared with the massive cholinergic innervation of the DA neurons, DA released within the PPTN may play an important part in controlling the activity of the PPTN.

Therefore, it is plausible that the PPTN provides important information for the computation of the reward prediction error by the DA neurons. Recent studies reported that PPTN signals sensory or motor rather than reward information of the task events. However, our previous study using a visually guided saccade task (VGST) requiring the animal to shift its gaze from a fixation to a saccade target demonstrated the existence of two groups of neurons within the PPTN, one responding to presentation of the fixation target to initiate the task in a manner that the response magnitude was correlated with the success and failure of individual task trials, while the other was responsive to the reward delivery [1, 3].

We hypothesized that the task performance-related neurons signal the reward prediction and those responsive to the reward delivery signal the reward outcome. This hypothesis was tested by studying the activity of PPTN neurons of the monkeys during visually guided saccade tasks rewarded with juice where the prediction of the task reward magnitude was cued by the shape of the fixation target [2].

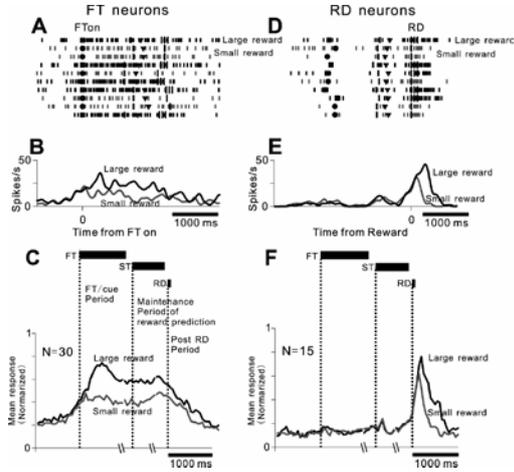
## II. Methods

In our recent study [2], the Japanese monkeys were trained on a visually guided saccade task (VGST) that required them to maintain fixation on a central fixation target (FT), and to make a horizontal saccade to a peripheral saccade target (ST) that was presented after the disappearance of the FT. Correct trials were rewarded randomly with either one or three drops of juice, and the magnitude (large or small) of the reward on a given trial was cued at the outset by the shape of the FT (square or circle). The trials began with the presentation of a fixation target (FT) at the center of the screen. At the start of each trial, the magnitude of the upcoming reward was cued by the shape of the FT, circles indicating a small reward and squares a large reward or vice versa.

## III. Results

We found that two distinct groups of neurons, the fixation target (FT) and reward delivery (RD) neurons carried reward information [2]. The FT neurons exhibited tonic activity starting after FT onset until reward delivery, whose activity was modulated by the expected reward size with

large-reward preference. The RD neurons exhibited phasic activity after reward delivery, whose activity was modulated by the received reward size with large-reward preference (Fig. 1).



**Figure 1 Responses of the FT and the RD neurons to task events**

**A, B**, a rastergram and peri-task event spike density function (SDF) for activities of a representative FT neuron for the 10 successive trials, aligned to fixation target (FT) onset. Black and gray conventions are for large and small reward trials, respectively. Square/circle and one/three thick bars in the rastergrams indicate FT onset and the time for reward delivery (RD) of large and small rewards, respectively. Thick Black lines and triangles indicate saccade target (ST) and saccade onset, respectively. **C**, The population SDF for 30 FT neurons. Responses were shown aligned to FT and saccade target (ST) onsets and the moment of RD. Conventions for large and small reward trials are the same in this as well as the succeeding figures as those for Figs. 1A and B. **D-F**, a similar rastergram and response histogram for a representative FT neuron and population response histograms for 15 FT neurons to Figs. 1A-C. Figures were modified from our recent paper [2].

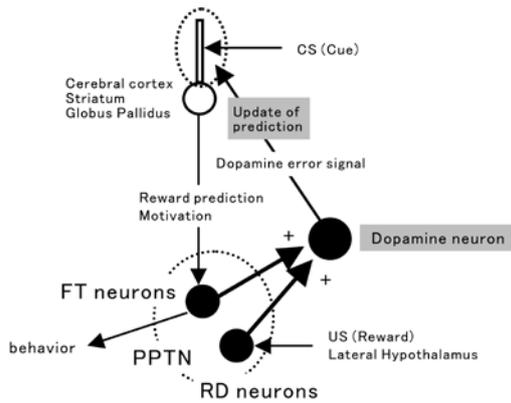
ROC analysis conducted for the magnitude-dependent FT and RD neuronal responses in the two-valued rewarded VGST, revealed that practically all of the individual FT and RD neurons reliably signaled the reward magnitude across the entire response period lasting from the FT presentation until the RD.

Mutual information analysis further showed that the FT ( $n = 30$ ) and RD neuronal ensemble ( $n = 15$ ) convey precision to encode the reward magnitude information (maximum information capacity, 2.6 and 3.5 bits, and 0.04 and 0.25 bits/neuron), which are comparable with those reported for the sensory (0.2 bits/neuron) and motor systems (0.05 bits/neuron).

All of these findings support the view that the FT and RD neuronal responses signal the predicted and actual reward magnitude, respectively. The FT neuronal response was sustained even after the disappearance of the FT/cue stimulus until the onset of the RD response that monitored the magnitude of the actual reward, and may work as the working memory to maintain reward magnitude prediction established at the time of FT/cue presentation until the time of actual reward delivery. Altogether, the PPTN feeds strong excitatory inputs to the midbrain dopamine neurons, through the two neuronal groups conveying the predicted and actual reward magnitude information that is needed for computing the reward prediction error. The high information capacity of the FT and RD neuronal signals encoding the reward magnitude may help to precisely compute the reward prediction error, and in consequence, the efficient execution of reinforcement learning.

#### IV. Discussion

Finally, we illustrated where and how to drive dopamine neuron and compute reward prediction error signal in Figure 2. Our recent observations support the view that the FT and RD neurons signal the predicted and actual reward magnitude, respectively. The continuation of the FT neuronal response after the disappearance of the cue until reward delivery indicates that the FT neurons may maintain the signals of the predicted reward from cue presentation until the RD neurons signal the actual reward magnitude. This study revealed that the strong excitatory inputs exerted by the PPTN on midbrain dopamine neurons convey the memory of the predicted reward and the signals of the actual reward, two essential elements needed for computing the reward prediction error. The high information capacity of the FT and RD neurons to signal the reward magnitude may help accurate computation of the reward prediction error and the efficient execution of reinforcement learning.



**Fig.2** Possible PPTN neuronal circuit for reinforcement learning

The computation of the reward prediction error requires a temporal memory of the predicted reward (established at cue onset and sustained until reward delivery) and subtraction of the actual reward from the predicted one. The reward predictive structures (cerebral cortex and striatum) may learn the cue-reward magnitude contingency during the training and task periods as a synaptic memory and recall that memory as the signals of the predicted reward magnitude at the time of cue presentation. These signals would be transferred to the FT neurons and stored as the working memory of the reward prediction until the time of reward delivery. Thus, the PPTN is an important center providing information of both reward prediction and the outcome of reward to DA neurons.

Moreover, our study addresses the broader science of memory: we demonstrated that the memory of the task reward is recalled as neuronal activity signaling the predicted reward magnitude, which is then compared with neuronal activity signaling the actual reward magnitude. To our knowledge, the mechanism whereby past memories, engrammed in the synaptic efficacy, are decoded into dynamic neural activity for comparison with the current neuronal activity, has remained totally unexplored, in spite of the fact that the inverse process of encoding the firing rate of current neural events into synaptic efficacy has been extensively studied by plasticity researchers. Thus, our study is the first demonstration that structural memories of past experience are decoded into dynamic neural activity and compared with that for the present experience. In fact, the PPTN is the site where both signals are simultaneously represented.

## References

- [1] **Y. Kobayashi**, Y. Inoue, M. Yamamoto, T. Isa, and H. Aizawa, "Contribution of pedunculopontine tegmental nucleus neurons to performance of visually guided saccade tasks in monkeys," *J Neurophysiol*, vol. 88, pp. 715-31, Aug 2002.
- [2] K. Okada, K. Toyama, Y. Inoue, T. Isa, and **Y. Kobayashi**, "Different pedunculopontine tegmental neurons signal predicted and actual task rewards," *J Neurosci*, vol. 29, pp. 4858-70, Apr 15 2009.
- [3] K. Okada, and **Y. Kobayashi**, "Characterization of oculomotor and visual activities in the primate pedunculopontine tegmental nucleus during visually guided saccade tasks," *Eur. J Neurosci*, vol 29 pp. 4858-4870, 2009.

# Spinal neural mechanisms as a foundation of Mobiligence

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**Abstract**—Our study has been supported by the Mobiligence project (Grant-in-Aid for scientific research from Japanese Ministry of Education, Culture, Sports, Science and Technology, Scientific Research of Priority Areas (No.454) between FY2006-2009. Overall objective of this project was to elucidate the function of spinal neural circuit for regulating voluntary movement by electrophysiological experiments using non-human primates. In each year, we have specifically focused on the intraspinal mechanism of sensory gating (2007), a network activity between spinal cord and working muscle and its role for generating muscle activities (2008), and roles of spinal interneurons for generating muscle activities during volitional movement (2009-10). Goal of the research group B was to elucidating the mechanisms of body-brain interaction that enables to generate and select the adaptable motor behaviors. The adaptable motor behavior should be generated at a various area of the central nervous system in animal. Among them, the spinal cord is physically most proximal to both muscle and sensory organ and known as the first relay of sensory signal and the final relay of motor command. Consequently, sensory gating at spinal level affects the sensory processing at higher center and modulation of motor command from descending system directly modify the programmed motor command. It was not known, however, that how the sensor and motor command are processed within the spinal cord and it was crucial to study this topics using experimental approach. Four years was obviously too short to obtain comprehensive answer to this important question. However, we showed that these questions are testable using experimental approaches of non-human primates.

I. Exploring a neural correlate of sensorimotor gating during voluntary movement in the spinal cord (FY2006).

**Introduction:** Normal motor behavior stimulates peripheral receptors, generating self-induced recurrent activity. For example, moving our limbs produces time-varying afferent input from cutaneous and proprioceptive receptors that is transmitted to the central nervous system (CNS), where it potentially interacts with motor commands and cognitive processes. The extent to which this re-afferent input is incorporated into ongoing motor and sensory processing remains a key issue in understanding mechanisms of voluntary movement and perception. Using new techniques to record the

activity of spinal interneurons in awake behaving monkeys, we found the most direct evidence to date that presynaptic inhibition operates in a behaviorally relevant manner during voluntary movement. Presynaptic inhibition reduces afferent input to the primate spinal cord during active voluntary movement, with potential effects on movement control and sensory perception.

## Experiment I: Modulation of monosynaptic afferent input during voluntary movement

We documented afferent input to C6-T1 spinal interneurons (n=284) using vertebral chamber (Fig.1) and their rate modulation in a monkey performing wrist flexion/extension movements in an instructed delay task. Cutaneous inputs (n=221) were evoked by electrical stimulation of the superficial radial nerve through a cuff electrode ( $2.6 \pm 1.5$  x threshold for an afferent volley recorded in another proximal cuff). Muscle inputs (n=87) were evoked by bipolar stimulation of forearm muscle afferents through wire electrode implanted in forearm muscles. The amplitude of the responses of interneurons and their mean firing rate was calculated separately for from peristimulus time histograms (PSTH) for twenty-four epochs of task. EMGs were recorded from 12-forearm muscles with pairs of indwelling electrodes. Cord dorsum potentials were recorded near the cord surface in each recording track (n=104) from the IN recording electrode.

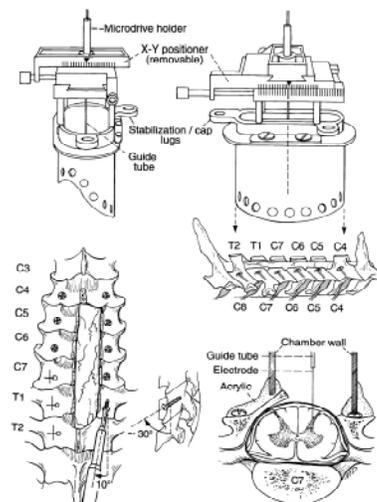


Fig. 1. Schematic diagrams of the surgical procedure for implanting a stainless steel chamber over a unilateral laminectomy of the C<sub>5</sub>-T<sub>1</sub> vertebrae and of the system for advancing metal recording electrodes through the chamber into the spinal cord

We found that the firing rate of interneuron which receive the cutaneous input (n=118) was higher ( $p < 0.01$ ) during movement than during hold or rest phases of flexion/extension movements. We also found that the responsiveness of interneurons from the stimulation on cutaneous afferent modulated as a function of task, and surprisingly the amplitude of responses were drastically decreased ( $p < 0.01$ ) during active movement. Since the first-order interneuron (n=38), which receive monosynaptic input from cutaneous afferents also exhibit the same characteristics ( $p < 0.01$ ), the depression of responsiveness during active movement was most likely to be induced by the presynaptic inhibition of afferent terminal onto the first-order interneurons. Furthermore, this suppression started 300- 400ms before the onset of muscle activity, suggesting that a part of suppression is induced by motor command, not only reafference. These results suggested that the peripheral information from cutaneous receptors are strongly gated during active movement by presynaptic inhibition. These mechanisms could be useful for brain to eliminate interference of peripheral sensory input with descending motor commands at spinal level.

#### Experiment II: Modulation of PAD during voluntary movement

Result from Experiment I indicates that presynaptic inhibition decreases the ability of afferent impulses to activate first-order spinal interneuron (IN) by descending motor command and natural stimulation to peripheral receptor. To further investigate this phenomenon, we examined the modulation of primary afferent depolarization (PAD) in monkeys performing a wrist flexion-extension task. We stimulated the superficial radial (SR) nerve (containing purely cutaneous afferents) and recorded evoked responses of single INs and local field potentials (LFP) in spinal cord [C6-T1]. When a monosynaptic response was observed (73 intraspinal sites; 55 sites near INs, 18 with LFPs), we delivered microstimuli (1-20 $\mu$ A; 3-10Hz) continuously through the recording microelectrode and recorded antidromic volleys (AVs) in the SR through a tripolar cuff electrode. Single stimuli sometimes evoked multiple (2-8) AVs, possibly by activating afferent terminals with different conduction velocity. We calculated the size (area) of individual volleys (n=270) and averaged in each behavioral epoch [rest, cue, delay, movement, hold, etc]. In specific phases of the behavioral task the size of most volleys (58%) increased or decreased significantly relative to control period, indicating that PAD was modulated in a task-dependent manner. AVs showing modulation had faster conduction velocities than those without modulation (57.04 $\pm$ 13.04 vs. 53.20 $\pm$ 13.65,  $p < 0.01$ ), suggesting the primary target of PAD modulation could be faster conducting fibers (i.e. A-beta). The size of many volleys increased during active wrist movement against an elastic load, when monosynaptic unit responses and LFPs decreased. These data suggest that low-threshold cutaneous input can be modulated

presynaptically by changing the amount of PAD in a behaviorally relevant way.

#### DISCUSSION

To detect informations about an external world, animal first make an active movement toward the environmental object of interest, and as a result, their peripheral receptor could capture the profile of object which is moved inside to their receptive field by movement. In this sequence of event, two kind of sensory information would be detected by brain; 1) information regarding to the target in their external world (object) and 2) sensory feedback generated by their own movement (reafference). Beside the former is essential for the feature detection of target, the later is essential for guiding their movement toward the target since they provides brain a real-time information about body position and current condition of movement. However, it is big challenge for brain to deal with reafference since they supply abundant information into central nervous system. For example, firing rate of single muscle afferent during locomotion achieves to 200Hz, and sum of input supplying from muscle afferents to CNS is estimated to be more than 800kHz.

In our series of study, we found that the presynaptic inhibition on peripheral cutaneous afferent was maximal during active movement period in a voluntary motor task. From an anatomical and physiological perspective, spinal cord is one of the first relay of peripheral input, and the sensory information transmitted to the first order spinal interneuron affects the computation process in post synaptic systems for guiding their movement and detecting feature of object significantly. Therefore, attenuating sensory input at very early stage of sensory processing may have an advantage for reducing computational load for CNS. Our hypothesis is that abundant informations conveyed by peripheral afferent activated active voluntary movement is needed to be attenuated for reducing computational load of postsynaptic systems, and presynaptic inhibition may effectively suppress the sensory feedback before they arrived at the very early stage of sensory processing.

#### II. Coherent activities between spinal cord and muscles in monkeys performing a precision grip task (FY2007).

INTRODUCTION: Rhythmic oscillatory activity has commonly been observed in the mammalian central nervous systems (CNS) and elucidating its significance in regulating behavior is an important question in neuroscience. The spinal cord is the first relay of both afferent and descending pathways and it is well known that spinal interneurons receive highly convergent input from a number of motor centers as well as peripheral afferents. It is reasonable to postulate therefore that oscillatory activity in the descending and afferent pathways is relayed through spinal interneurons, and that spinal interneurons can affect, and can be affected by this oscillatory activity. Therefore it is important to know if coherent oscillations exist in spinal interneurons during movement.

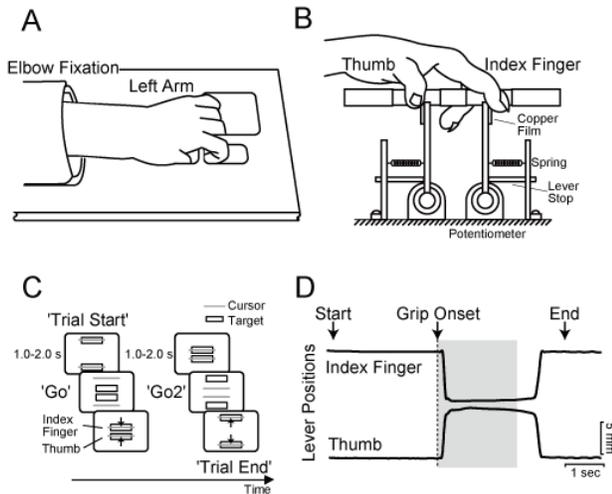


Fig.2 Experimental setup. A,B: diagrams of the custom-made manipulandum for the precision grip task in top view (A) and lateral view (B). C: Sequence of a trial. Lever positions were reported to the monkey as two visual cursor signals on the computer display (gray bars). Two target boxes were also displayed (black rectangles). D: Example of finger movements during a single trial. Upper arrows indicate the time point of each task event. Two traces show lever positions (upper: index finger, lower: thumb). Shaded area indicates the time range where frequency analyses were performed (from 0 to 2.048 sec after 'Grip Onset').

However, no previous reports have examined this question in awake, behaving animals. The aims of this study were to determine if the oscillations are present in areas of spinal cord containing spinal interneurons and, if so, are they coherent with similar activity in forelimb muscles during voluntary movement. To this end, we have recorded cervical spinal cord LFPs and forelimb muscle EMGs in monkeys performing a precision grip task.

**RESULTS:** Two monkeys were trained to perform precision grip task with his thumb and index finger (Fig.2). After behavioral training was complete, three separate surgeries were performed to implant a head restraint, a recording chamber over the cervical spinal cord, and EMG wire electrodes into multiple forelimb muscles. LFPs were recorded from 22 sites in the cervical spinal cord (C5-C8, 15 from monkey A and 7 from monkey U). From 299 LFP-EMG pairs recorded, 131 pairs were eliminated because of significant EMG-EMG cross-talk. Consequently, further analysis was performed on 168 LFP-EMG pairs (154 and 14 pairs from monkey A and U, respectively). Among the LFP power spectra recorded from 22 intraspinal sites, 14 (64%) LFPs showed similar peaks between 10 and 40 Hz. Among the 168 LFP-EMG pairs, 68 pairs (40%) showed at least one significant peak in their coherent spectrum (60/154 and 8/14 from monkey A and U, respectively). Quantitative comparison amongst these coherence spectra were made by measuring the width of the significant peak in each spectrum. We have concluded that the spinomuscular coherence occurred in two different modes, narrowband coherence (NB) and broadband coherence (BB). The dominant coherence frequency was

restricted to 10-40 Hz in NB and occurred at all frequencies examined (10-95 Hz) in BB. To further characterize these two modes of coherence, they were analyzed with respect to depth of the recording sites in the spinal cord. The proportion of LFP-EMG pairs with significant coherence (NB or BB) was not uniformly distributed with depth in the spinal cord, rather it was unimodal with a peak at 2500  $\mu\text{m}$ . Interestingly, the NB was present at every depth while the BB was restricted to depths between 2000-3000  $\mu\text{m}$ . This difference indicates that the BB is restricted to the ventral portion of spinal cord whereas the NB can be found throughout dorsal and ventral spinal cord. A part of these observations has been confirmed in the second monkey.

**CONCLUSION:** we found the oscillatory LFPs in the spinal grey matter of monkeys performing a precision grip task which was coherent with forelimb muscle activity in either a restricted or broad frequency range. Spinomuscular coherence could reflect oscillatory input from descending and/or peripheral afferents. Elucidating mechanisms underlying spinomuscular coherence will be important for understanding the role of motor system oscillatory activity in controlling voluntary movements.

### III. Contribution of spinal interneurons for controlling grasping movement (FY2008-2009).

**INTRODUCTION:** More than a half century ago A.N. Bernstein observed that "dexterity" residing in human limb motion emerges from accumulated involvement of multi-joint movements in surplus DOF. Grasping movement is a typical multi-joint movement that require to control 39 different intrinsic or extrinsic hand muscles. Functional muscle synergy has been proposed for the regulation of these redundant DOF, but the neural correlate that generate this synergy is not well established. In this study, we examined the potential involvement of spinal cord neurons for generating synergistic activity of hand muscles during grasping movement in non-human primates.

**METHODS:** A monkey was trained to perform precision grip task using a custom-made manipulandum. The monkey inserted its thumb and index finger through separate holes in a horizontal plate to access the levers of the manipulandum. Fingers 3-5 were inserted through another hole. The manipulandum comprised two spring-loaded levers. After behavioral training was complete, three separate surgeries were performed to implant a head restraint, a recording chamber over the cervical spinal cord, and EMG wire electrodes into multiple forelimb muscles. During each recording session, the monkey's head was fixed to the chair with plastic rods and a glass-insulated tungsten microelectrode (impedance 1 to 2  $\text{M}\Omega$  at 1 kHz) was inserted into cervical spinal cord (Fig.1). The position of the electrode was controlled by using a hydraulic microdrive and a custom-made X-Y stage, both of which were mounted on the recording chamber. A silver-ball electrode was also inserted

into spinal chamber as a reference electrode and placed on the scar tissue overlying the cord surface. In addition, output from the amplifier was high-pass filtered (0.3 kHz – 10 kHz) for monitoring action potentials from single spinal neurons.

**RESULTS:** Among 199 neurons recorded from cervical spinal cord (C6-T1), a majority of the neurons (160 neurons, 80%) showed movement-related modulations of their firing rate during grip (138/199, 69%), hold (81/199, 41%), and release period (125/199, 63%). We compiled STAs of rectified EMGs for the 196 neurons (3920 neuron–muscle pairs), after careful rejection of motoneuron recordings. Among them, thirty neurons produced 56 significant STA effects (51 facilitations and 5 suppressions) in hand and arm muscles. The STA effects generated by electrical cross-talk of EMG signals were excluded from data pool. To discriminate pure post-spike effect from other synchrony effects, we used two criteria – onset latency and peak width at half maximum (PWHM). STA effects that have (1) a longer onset latency than the possible earliest latency estimated with intra-spinal microstimulation (single pulse, <30uV, 4.7ms for hand muscles and 3.5ms arm muscles), and (2) a narrower PWHM less than 7ms were determined as pure post-spike effects. Using these criteria, 48 STA effects produced by 21 neurons were determined as pure post-spike effects from premotor interneurons (PreM-INs).

The majority of these 21 PreM-INs (13 neurons, 62%) produced post-spike effects in multiple muscles rather than an effect on single muscle. The size of muscle field (i.e. number of muscles on which single neuron had pure post-spike effects) was  $2.3 \pm 1.4$  in average. The type of post-spike effects was mainly facilitative (19 neurons) and only two neurons had suppressive effects. No neuron simultaneously had both of facilitative and suppressive effects. The muscle fields of single neuron were frequently observed within intrinsic hand muscles (6/13 neurons, 46%) and between intrinsic and extrinsic hand flexor (4/13 neurons, 31%), which were synergistically activated during the precision grip task. These results indicate that single spinal INs can produce co-activation of synergistic muscles.

**DISCUSSION:** Aims in this study was to elucidate the pattern of firing activity of spinal interneurons during precision grip performed by primate, and characterize the “muscle field” of each spinal neurons by means of spike-triggered averaging of EMG signals. We believe the result described above meets these objective in term of four points.

1. More than 80% of spinal neurons recorded showed a task-dependent activity during precision grip. This is a first study that successfully recorded an activity of spinal neuron in monkeys performing grasping movements. We found it possible to make a stable recording of spinal interneurons in monkeys behaving relatively unrestricted movement. The finding that a majority of neurons showed a task-related firing activity may suggest that spinal neurons may be involved in a various aspect of grasping control system, not only modulating an activity of single muscle/ joints.

2. Muscle field of spinal interneurons were restricted within an intrinsic hand muscle or extrinsic hand muscles. This results may suggest that spinal cord may be involved in the organization of synergistic movement between the muscles that is essential for generating grasping force. As a next step, it is essential to examine the functional significance of spinal muscle field by examining the correlations between firing characteristics and their muscle field of the last-order spinal interneurons.

3. Spinal last-order interneurons showed a muscle field with 2 to 3 finger muscles. It seems that the spinal muscle field is wider in the grasping movement than that in the wrist movement. This may suggest that spinal neuron has a greater contribution for creating muscle synergy of hand muscle than that of wrist muscles. To confirm this hypothesis, it is important to compare the size of muscle field of spinal interneurons in single monkeys performing both wrist and finger movements.

4. Majority of last-order INs showed post-spike facilitation. One may suggest that the muscle synergy created by spinal neurons mainly induced by spinal excitatory last-order interneurons. However, relative strength or number between excitatory and inhibitory interneurons is difficult to estimate by STA method applied in this study. Rather, it is also likely that the inhibitory last-order interneurons may optimize the synergistic pattern generated by excitatory last-order interneurons corresponding to different requirement of different movement epochs.

#### IV. FUTURE DIRECTION

The spinal cord is often regarded as a separate structure from brain that functions as a simple relay between brain and body. However, results described above are clearly showing that the spinal cord is one of key center for the sensorimotor transformation and exhibiting synergistic limb movement during voluntary movement. These results should be incorporated into the framework of Mobiligence, and into the synthetic understanding of biological movements.

#### ACKNOWLEDGEMENT

We thank all of members of “idouchi” who gave us a stimulating discussion and interdisciplinary viewpoints.

# Movement Control by the Basal Ganglia

Atsushi Nambu

**Abstract**—During voluntary movements, information originating from the motor cortices is processed in the basal ganglia and returns to the motor cortices via the thalamus. The subthalamic nucleus (STN) and the striatum, the input structures of the basal ganglia, receive direct excitatory cortical inputs and send projections to the output nuclei, the internal segment of the globus pallidus (GPi) and the substantia nigra pars reticulata (SNr), via the following three pathways: 1) cortico-STN-GPi/SNr *hyperdirect* pathway, 2) cortico-striato-GPi/SNr *direct* pathway, 3) cortico-striato-external pallido (GPe)-STN-GPi/SNr *indirect* pathway. Information through these three pathways dynamically controls the activity of the thalamus and cortex, and releases only the selected motor program at the selected timing. Based on such *dynamic* model of the basal ganglia functions, the pathophysiology of hypokinetic and hyperkinetic movement disorders, such as Parkinson disease and dystonia, and the mechanism of the effectiveness of stereotaxic surgery can be explained by changes in the activity of the thalamus and cortex in the *temporal and spatial* domains.

## I. INTRODUCTION

FOR the control of voluntary movement, the interactions between the cerebral cortex and the basal ganglia through the cortico-basal ganglia loop are essential. The basal ganglia receive cortical inputs, process the information and send it back to the original cerebral cortex via the thalamus to assist the cortical activity (Fig. 1). The internal segment of the globus pallidus (GPi) and the substantia nigra pars reticulata (SNr) are the output nuclei of the basal ganglia. On the other hand, the striatum is the input station and receives direct excitatory cortical inputs. In the current model of basal ganglia organization, the striatum projects to the output nuclei, via two major projection systems, the *direct* and *indirect* pathways [1]. The direct pathway arises from GABAergic striatal neurons containing substance P and projects monosynaptically to the GPi/SNr. The indirect pathway arises from GABAergic striatal neurons containing enkephalin and projects polysynaptically to the GPi/SNr by way of a sequence of connections involving the external

segment of the globus pallidus (GPe) and subthalamic nucleus (STN).

## II. CORTICO-STN-GPi/SNR HYPERDIRECT PATHWAY

The cerebral cortex projects topographically to the STN, as well as to the striatum [2, 3]. Thus, recent studies propose the idea that the STN is another input station of the basal ganglia, forming the cortico-STN-GPi/SNr *hyperdirect* pathway [4] whose conduction velocity is faster than those of the direct and indirect pathways (Fig. 1). Indeed, stimulation of the motor cortices induces an early, short-latency excitation, followed by an inhibition and a late excitation in monkey GPe, GPi and SNr neurons [5-8]. The early excitation in the GPi is derived from the cortico-STN-GPi/SNr hyperdirect pathway, while the inhibition and late excitation are mediated by the cortico-striato-GPi/SNr direct and cortico-striato-GPe-STN-GPi/SNr indirect pathways, respectively.

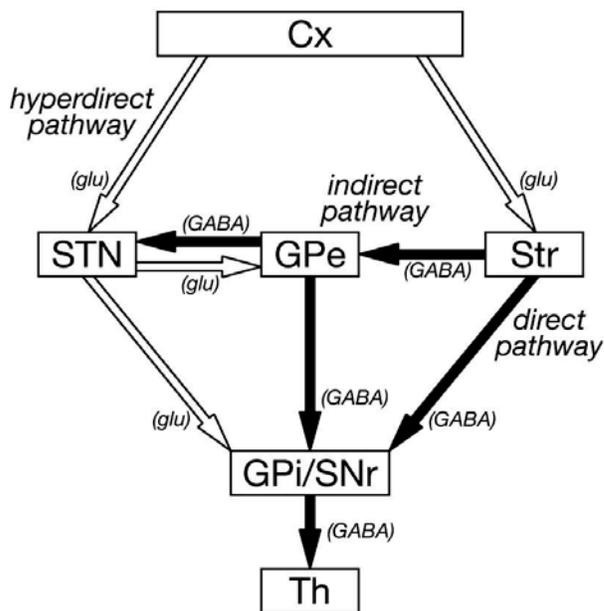


Fig. 1. Basic circuitry of the basal ganglia, comprising the Cx-STN-GPi/SNr *hyperdirect*, Cx-Str-GPi/SNr *direct* and Cx-Str-GPe-STN-GPi/SNr *indirect* pathways. Open and filled arrows represent excitatory glutamatergic (glu) and inhibitory GABAergic (GABA) projections, respectively. Cx, cerebral cortex; GPe, external segment of the globus pallidus; GPi, internal segment of the globus pallidus; SNr, substantia nigra pars reticulata; STN, subthalamic nucleus; Str, striatum; Th, thalamus. (Modified from [4])

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### III. ACTIVITY OF GPi NEURONS

The GPi receives topographical inputs from the cerebral cortex through the hyperdirect, direct and indirect pathways. GPi neurons in the forelimb region of the motor territory (ventral two-thirds of caudal GPi) change their activity, either inhibitory or excitatory, in relation to forelimb movements [9-12]. These changes are presumably the result of a combination of inhibitory GABAergic inputs from the striatum, and excitatory glutamatergic inputs from the STN, reflecting information through the direct, indirect and hyperdirect pathways. We do not know much about the extent of the contribution of each input to GPi activity during movements. However, the interesting finding is that GPi activity during voluntary limb movements always displays an increase rather than a decrease in discharge [9-12], suggesting a large contribution of inputs from STN.

### IV. DYNAMIC MODEL OF THE BASAL GANGLIA FUNCTIONS

GPi/SNr neurons are GABAergic and fire at high frequency, thus neurons in their target structures, such as the thalamus, are inhibited continuously (Fig. 2). When striatal neurons are activated by cortical inputs, the striatal neurons inhibit GPi/SNr activity through the striato-GPi/SNr direct pathway. The continuous inhibition from the output nuclei to the target structures is transiently removed (disinhibition), and thalamic neurons are activated. The increased activity of the thalamus is transmitted to the motor cortex, and finally evokes the selected motor program. On the other hand, signals through the hyperdirect and indirect pathways have excitatory effects on the GPi/SNr, thus have inhibitory effects on thalamic neurons. Considering the respective axonal

conduction velocities, signals through the hyperdirect pathway first actively inhibit thalamic neurons, then those through the direct pathway disinhibit them, and finally those through the indirect pathway inhibit them again. Thus, signals through the hyperdirect and indirect pathways make clear initiation and termination of the selected motor program [4].

In addition to such a temporal aspect, the enhancement by differential inputs through the hyperdirect, direct and indirect pathways may work in spatial domain as well. The *center-surround model* of basal ganglia functions proposes focused selection of an appropriate motor program and inhibition of competing motor programs [4, 13-15] (Fig. 2). Thalamic neurons are usually inhibited by continuous GABAergic inputs from the GPi. Signals through the direct pathway inhibit a specific group of GPi neurons in the center area, and thalamic and cortical neurons are released from inhibition and become active, resulting in the release of the selected motor program. On the other hand, signals through the hyperdirect and indirect pathways excite other groups of GPi neurons in the surrounding area, and increases inhibition on thalamic neurons mediating other competing motor programs. Inhibition in the center area of the GPi by striatal GABAergic inputs and excitation in the surrounding area by glutamatergic STN inputs help the execution of the selected motor program and the inhibition of other competing motor programs.

Based on the *temporal and spatial* inputs to the target structures through the hyperdirect, direct and indirect pathways, only the selected motor program is executed at the selected timing, and other competing motor programs are cancelled.

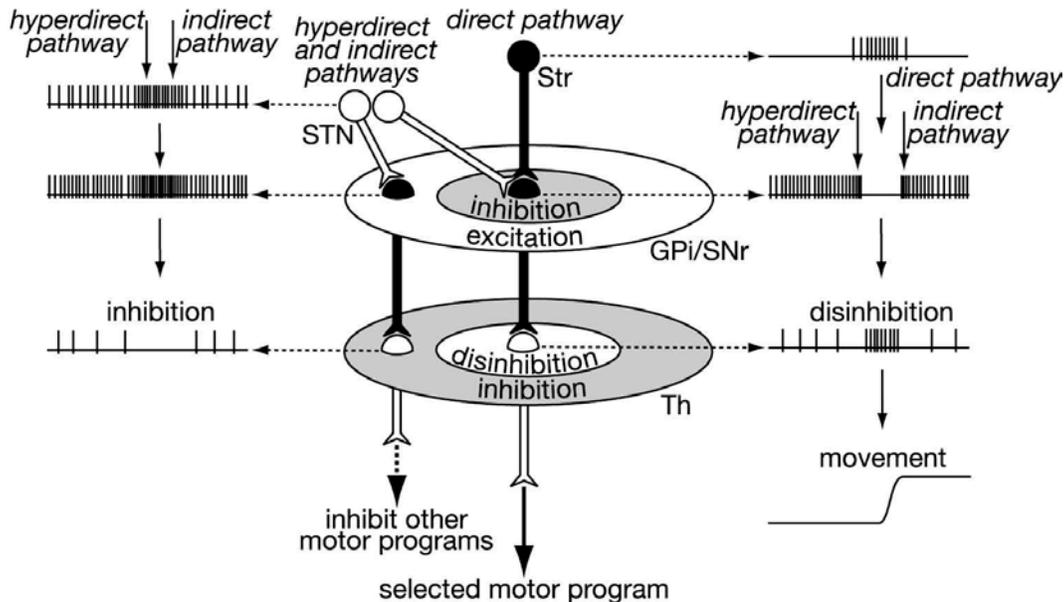


Fig. 2. Spatial and temporal distributions of basal ganglia activity during voluntary movement based on the dynamic model. Signals through the direct pathway inhibit GPi neurons in the center area, activate thalamic neurons by disinhibition and finally release a selected motor program. On the other hand, signals through the hyperdirect and indirect pathways have broad excitatory effects on GPi neurons in temporal and spatial domains, make clear initiation and termination of the selected motor program, and inhibit other unnecessary competing motor programs. Open and filled neurons represent excitatory glutamatergic and inhibitory GABAergic neurons. (Modified from [16])

## V. PATHOPHYSIOLOGY OF MOVEMENT DISORDERS

The neural mechanisms underlying hypokinetic and hyperkinetic movement disorders are currently explained as changes in the *static* state of the basal ganglia by the standard model. An impaired balance of activity between the direct and indirect pathways causes an increase or decrease in the mean firing rate of GPi/SNr neurons [17, 18]. For example, in Parkinson disease, activity along the indirect pathway is increased and activity along the direct pathway is reduced. Both changes enhance the mean firing rate of GPi/SNr neurons, suppress the activity of thalamic and cortical neurons and finally cause akinesia. On the other hand, in dystonia, activity along both direct and indirect pathways is increased, reduces the mean firing rate of GPi/SNr neurons, excites the activity of thalamic and cortical neurons by disinhibitory mechanism and finally cause involuntary movements.

The dynamic model can better explain the pathophysiology of hypokinetic and hyperkinetic movement disorders by introducing the temporal and spatial aspects of the basal ganglia functions (Fig. 3). In normal monkeys, cortical stimulation evokes a triphasic response composed of an early excitation, an inhibition and a late excitation in GPi neurons. In monkeys rendered parkinsonian by infusion of 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP), the duration of the inhibition in GPi neurons evoked by cortical stimulation is reduced, and the amplitude of early and late excitations is increased. The intravenous injection of L-dopa transiently improves parkinsonian akinesia, and the cortically-evoked response pattern in the GPi is restored to the normal triphasic pattern. These observations suggest that in parkinsonian state, when a voluntary movement is about to be initiated by cortical mechanisms, signals through the hyperdirect and indirect pathways expand and suppress larger areas of the thalamus and cortex than in the normal state, and a signal through the direct pathway is reduced (Fig. 3, left). Thus, smaller areas of the thalamus and cortex are disinhibited for shorter period of time than in the normal state, and not only the competing motor program, but also the selected motor program cannot be released, resulting in akinesia of Parkinson disease.

On the other hand, cortical stimulation produces long inhibitions in the GPe/GPi of monkeys during hemiballism, which is induced by STN blockade. In transgenic mouse model of dystonia, cortical stimulation also induces long inhibition in the GPe/GPi [19]. Thus, cortically-evoked long inhibition is considered to be a common feature of hyperkinetic disorders. Even tiny neuronal activity originating in the cortex is transmitted through the basal ganglia circuitry and finally induces a strong and long-lasting inhibition in the wide areas of the GPi (Fig. 3, right). Therefore, the wide areas of the thalamus and cortex mediating both the selected and competing motor programs are activated in an uncontrollable manner, resulting in involuntary movements observed in hyperkinetic disorders.

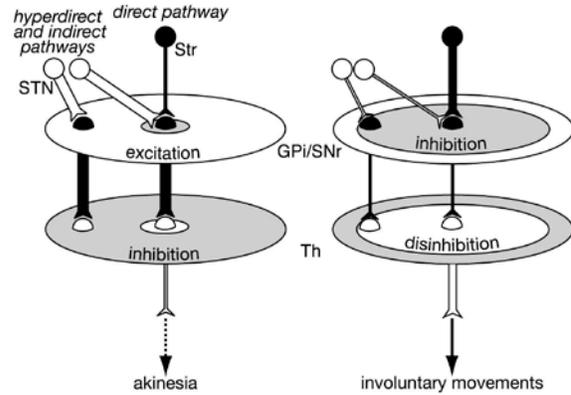


Fig. 3. Schematic diagram showing the activity changes in the basal ganglia during movement disorders. Increased signals through the hyperdirect and indirect pathways and a reduced signal through the direct pathway result in reduced disinhibition in the Th/Cx, leading to hypokinetic disorders (left). An increased signal through the direct pathway and reduced signals through the hyperdirect and indirect pathways result in increased disinhibition in the Th/Cx, leading to involuntary movements observed in hyperkinetic disorders (right).

## VI. MECHANISM OF THE EFFECTIVENESS OF STEREOTAXIC SURGERY

Recent advances in stereotaxic surgery have highlighted the STN as a target structure. In monkeys and humans, a lesion or high frequency stimulation (HFS) of the STN can ameliorate parkinsonian motor symptoms [20-23]. In our experiments, the blockade of the STN activity by the local injection of GABA<sub>A</sub> agonist muscimol also improves motor activity of parkinsonian monkeys. The blockade of the STN diminishes the early and late excitations evoked by cortical stimulation and prolongs the duration of the inhibition in the GPi. According to the dynamic model, a main cause of akinesia is a reduced disinhibition in the thalamus and cortex during movements, and the blockade of the STN restores the disinhibition in the cortex and thalamus during movement and releases the selected motor program. On the other hand, the mechanism of STN-HFS is not clear, and whether HFS excites or inhibits STN neuronal activity is open to argument [23].

## VII. CONCLUDING REMARKS

I introduced the dynamic model of the basal ganglia functions: Information through the hyperdirect, direct and indirect pathways dynamically controls the activity of the thalamus and cortex and releases only the selected motor program at the selected timing. The dynamic model can also explain the pathophysiology of movement disorders and the mechanism of the effectiveness of stereotaxic surgery. The dynamic model will lead us not only to better understanding of the normal functions of the basal ganglia, but also to better treatments of movement disorders.

REFERENCES

- [1] Alexander GE, Crutcher MD (1990) Functional architecture of basal ganglia circuits: neural substrates of parallel processing. *Trends Neurosci* 13 : 266-271
- [2] Hartmann-von Monakow K, Akert K, Künzle H (1978) Projections of the precentral motor cortex and other cortical areas of the frontal lobe to the subthalamic nucleus in the monkey. *Exp Brain Res* 33 : 395-403
- [3] Nambu A, Takada M, Inase M, Tokuno H (1996) Dual somatotopical representations in the primate subthalamic nucleus: evidence for ordered but reversed body-map transformations from the primary motor cortex and the supplementary motor area. *J Neurosci* 16 : 2671-2683
- [4] Nambu A, Tokuno H, Takada M, (2002) Functional significance of the cortico-subthalamo-pallidal “hyperdirect” pathway. *Neurosci Res* 43 : 111-117
- [5] Yoshida S, Nambu A, Jinnai K (1993) The distribution of the globus pallidus neurons with input from various cortical areas in the monkey. *Brain Res* 611 : 170-174
- [6] Nambu A, Tokuno H, Hamada I, Kita H, Imanishi M, Akazawa T, Ikeuchi Y, Hasegawa N (2000) Excitatory cortical inputs to pallidal neurons via the subthalamic nucleus in the monkey. *J Neurophysiol* 84 : 289-300
- [7] Kita H, Nambu A, Kaneda K, Tachibana Y, Takada M (2004) Role of ionotropic glutamatergic and GABAergic inputs on the firing activity of neurons in the external pallidum in awake-monkeys. *J Neurophysiol* 92 : 3069-3084
- [8] Tachibana Y, Kita H, Chiken S, Takada M, Nambu A (2008) Motor cortical control of internal pallidal activity through glutamatergic and GABAergic inputs in awake monkeys. *Eur J Neurosci* 27 : 238-253
- [9] Georgopoulos AP, DeLong MR, Crutcher MD (1983) Relations between parameters of step-tracking movements and single cell discharge in the globus pallidus and subthalamic nucleus of the behaving monkey. *J Neurosci* 3 : 1586-1598
- [10] Hamada I, DeLong MR, Mano N (1990) Activity of identified wrist-related pallidal neurons during step and ramp wrist movements in the monkey. *J Neurophysiol* 64 : 1892-1906
- [11] Nambu A, Yoshida S, Jinnai K (1990) Discharge patterns of pallidal neurons with input from various cortical areas during movement in the monkey. *Brain Res* 519 : 183-191
- [12] Turner RS, Anderson ME (1997) Pallidal discharge related to the kinematics of reaching movements in two dimensions. *J Neurophysiol* 77 : 1051-1074
- [13] Mink JW, Thach WT (1993) Basal ganglia intrinsic circuits and their role in behavior. *Curr Opin Neurobiol* 3 : 950-957
- [14] Mink JW (1996) The basal ganglia: focused selection and inhibition of competing motor programs. *Prog Neurobiol* 50 : 381-425
- [15] Hikosaka O, Takikawa Y, Kawagoe R. (2000) Role of the basal ganglia in the control of purposive saccadic eye movements. *Physiol Rev* 80 : 953-978
- [16] Nambu A (2007) Globus Pallidus internal segment. In: Tepper JM, Abercrombie ED, Bolam JP (ed) *GABA and the Basal Ganglia: From Molecules to Systems*, Prog Brain Res 160. Elsevier, Amsterdam, pp135-150
- [17] Albin RL, Young A B, Penney, JB (1989) The functional anatomy of basal ganglia disorders. *Trends Neurosci* 12 : 366-375
- [18] DeLong MR (1990) Primate models of movement disorders of basal ganglia origin. *Trends Neurosci* 13 : 281-285
- [19] Chiken S, Shashidharan P, Nambu A (2008) Cortically evoked long-lasting inhibition of pallidal neurons in a transgenic mouse model of dystonia. *J Neurosci* 28: 13967-13977
- [20] Bergman H, Wichmann T, DeLong MR (1990) Reversal of experimental parkinsonism by lesions of the subthalamic nucleus. *Science* 249 : 1436-1438
- [21] Hashimoto T, Elder CM, Okun MS, Patrick SK, Vitek JL (2003) Stimulation of the subthalamic nucleus changes the firing pattern of pallidal neurons. *J Neurosci* 23 : 1916-1923
- [22] Jahanshahi M, Ardouin CMA, Brown RG, Rothwell JC, Obeso J, Albanese A, Rodriguez-Oroz MC, Moro E, Benabid AL, Pollak P, Limousin-Dowsey P (2000) The impact of deep brain stimulation on executive function in Parkinson's disease. *Brain* 123 : 1142-1154
- [23] Lozano AM, Dostrovsky J, Chen R, Ashby P (2002) Deep brain stimulation for Parkinson's disease: disrupting the disruption. *Lancet Neurol* 1 : 225-231

# Quantitative Evaluation of Neurological Diseases based on Pathological Patterns of the Muscle Activities

Jongho Lee, Yasuhiro Kagamihara and Shinji Kakei

**Abstract**—In this study, we propose a novel method to make a quantitative evaluation of neurological disorders using a wrist movement. Specially, based on EMG signals, we quantitatively evaluated the movement disorders for Parkinson’s disease and cerebellar diseases from the motor command level.

As an experimental task, we asked subjects to perform smooth pursuit wrist movement, in which the subjects follow a smoothly moving target with a cursor. We recorded movement of the wrist joint and EMG signals of four wrist prime movers. The participants included five patients with cerebellar diseases, four patients with Parkinson’s disease and six normal controls. In order to evaluate movement disorders from the motor commands level, we captured characteristic patterns of the muscle activities for patients with cerebellar disorders and patients with Parkinson’s disease. We found three useful parameters that characterize pathological patterns of the muscle activities. In addition, we found that these parameters, if combined appropriately, are useful to characterize complex patterns of muscle activities in a way easy to be recognized visually. In other words, the high-dimensional parameter space is also useful to evaluate effects of a medical treatment as a shift toward or away from the normal control in the parameter space. Consequently, it is expected that our proposed methods will be useful for a navigation system of medical treatments or rehabilitation based on the motor commands.

## I. INTRODUCTION

SO far, some researchers tried to evaluate arm movements in various conditions [1,2]. They captured some features of movement disorders in patients with neurological diseases such as Parkinson’s disease or cerebellar atrophy. However, the scope of these analyses was limited to movement kinematics. The problem here is that the movement kinematics, in general, cannot specify its causal muscle activities (i.e. motor commands) due to the well-known redundancy of the musculo-skeletal system. Thus, in order to understand central mechanisms for generation of pathological movements, it is necessary to capture causal anomaly of the motor commands directly, rather than to observe the resultant movement indirectly [3,4]. For that

This work has been partially supported by a Grants-in-Aid for Scientific Research on Priority Areas “Emergence of Adaptive Motor Function through Interaction between Body, Brain and Environment” from the Japanese Ministry of Education, Culture, Sports, Science and Technology (SK). This work was also supported by the Tokyo Metropolitan Organization for Medical Research (SK) and MEXT KAKENHI 21700229 (JL).

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purpose, we identified causal relationship between wrist movement and activities of as few as four wrist prime movers [5]. With our method, it was possible to establish one-to-one relationship between movement disorders and causal activities of the muscles.

In this study, for the next step, we propose a novel method to evaluate neurological disorders directly from motor commands. Particularly, based on EMG signals, we captured characteristic patterns of the muscle activities for patients with cerebellar disorders and patients with Parkinson’s disease. We first extracted three parameters characterizing the variability and the effectiveness of muscle activities. Then, we confirmed the effectiveness of these parameters for a quantitative evaluation of neurological disorders. In other words, we found that these parameters, if combined appropriately, are useful to characterize complex patterns of muscle activities for each disease in a way easy to be recognized visually. Therefore, it is expected that our proposed methods will be useful for a navigation system of medical treatments or rehabilitation based on the high-dimensional parameter space.

## II. EXPERIMENTAL METHOD

### A. Subject and Experimental Setup

Five patients clinically diagnosed as cerebellar disorders (average age was 64.0, two patients were diagnosed as spinocerebellar degeneration, two patients as multi-system atrophy and one patient as multiple sclerosis), four patients clinically diagnosed as Parkinson’s disease (average age was 70), and six normal controls who didn’t have any history of neurological disorders (average age was 47.17) participated as the subjects. All participants gave an informed written consent, and the local ethical committees approved this study.

Fig. 1(a) shows the outline of the experimental setup. Subjects sat on a chair and grasped a manipulandum with his/her right hand. The forearm was comfortably supported with an armrest. Movement of the wrist joint is measured with 2 position sensors of the manipulandum at 2 kHz sampling rate, and the wrist position is linked to the position of the cursor on the computer display. In other words, the manipulandum worked as a mouse for the wrist joint. As an experimental task, we asked subjects to perform pursuit wrist movements, in which the subjects follow a smoothly moving target with a cursor (Fig. 1(b)). To initiate a trial, the subject placed the cursor inside the target, which was positioned at the upper left ( $X=-10^\circ$ ,  $Y=8^\circ$ ) of the screen.

After a fixed hold period of 4 seconds, the target moved by making the path of the figure 2 at the constant speed (mean velocity = 6.2deg/sec). At that time, the subjects had to enter the cursor into the moving target continuously. After practicing 2 or 3 times in order to understand this task sufficiently, each subject performed this task 5 times.

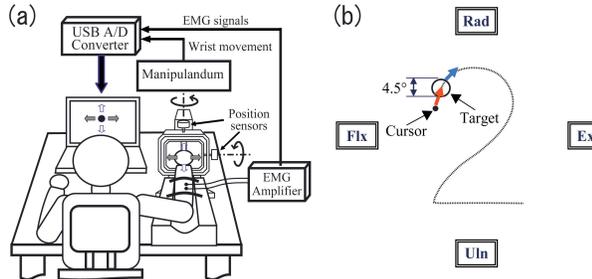


Fig. 1 Outline of the experimental setup (a), and pursuit wrist movement as the experimental task (b). To make the wrist movement task, the subject holds the forearm in the neutral position, midway between full pronation and full supination.

During the task, four channels of EMG signals and two degree of freedom wrist movements were sampled and recorded at 2 kHz. EMG signals were recorded with Ag-AgCl surface electrodes and amplified differentially. We recorded the EMG signals from four wrist prime movers: extensor carpi radialis (ECR), extensor carpi ulnaris (ECU), flexor carpi ulnaris (FCU) and flexor carpi radialis (FCR). Specially, based on pulling direction for each muscle [6], the position of each electrode was adjusted for each subject to maximize EMG signals for a specific movement of each muscle. In a few healthy control volunteers, we confirmed effectiveness of the adjustment with high correlation between the surface EMG signals and the corresponding EMG signals recorded with needle electrodes from the same muscles identified with evoked-twitches. Overall, we can analyze relationship between movements of the wrist joint and activities of the four wrist muscles, while the subjects perform the task using the manipulandum

### B. Normalization of EMG Signals

It is well known that EMG signals are closely correlated with activities of  $\alpha$  motor neurons, which represent the final motor commands from the CNS. These motor commands generate muscle contraction, which results in muscle tension. It is established that a second order, low-pass filter is sufficient for estimating muscle tension from the raw EMG signal [7]. However, though the low-pass filtered EMG signal is proportional to muscle tension, the proportional constant varies due to variability of skin resistance or electrode position on the muscle for each recording. Therefore, for a quantitative analysis, it is necessary to normalize the EMG signals. For this purpose, we asked the subject to generate isometric wrist joint torque for the PD of each muscle. Namely, for each muscle, we set the amplitude

of the EMG signals for 0.8 Nm of isometric wrist joint torque as 1. Then, the normalized EMG signals were digitally rectified and then filtered with a low-pass filter of a second order (cut-off frequency: 2.2Hz) [8]. Most critically, we considered the filtered EMG signals as muscle tensions, and used them to estimate the wrist joint torque [7,8].

## III. RESULTS

### A. Quantification of pathological patterns of muscle activities

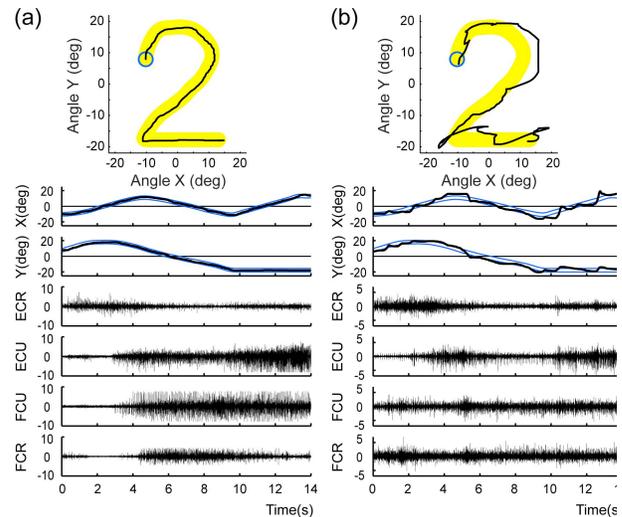


Fig. 2 Trajectories and EMG signals for the pursuit movement. (A) An example for a normal control. The inset demonstrates a trajectory of the wrist joint for a pursuit movement. The top two traces show X-axis and Y-axis components of the wrist joint angle. The bottom four traces show EMG signals of ECR, ECU, FCU, FCR. (B) A corresponding example recorded from a cerebellar patient.

Fig. 2 shows trajectories and EMG signals of the pursuit movement recorded from a normal control and a cerebellar patient. As shown in Fig. 2(a), the normal control followed the moving target very smoothly, by activating the proper muscle corresponding to the movement direction. In contrast, for the cerebellar patient (Fig. 2(b)), the pursuit movement was continuously disturbed by improper timing of agonist selection and/or co-contraction of both agonists and antagonists. In other words, the trajectory of the pursuit for the cerebellar patient was not smooth, showing an irregular stepwise tracking pattern which conformed to a position tracking pattern [9]. In other words, in order to make a pursuit wrist movement, it is desirable to change muscle activities smoothly, because the target moves smoothly. In addition, it is also desirable to maximize contrast between activities of agonist and antagonist muscles to minimize energy consumption for a movement. Therefore, in order to evaluate the pursuit movement directly from motor commands, we extracted three parameters characterizing the variability and the effectiveness of muscle activities: “Variability of Total Contraction” (VTC),

“Directionality of Muscle Activity” (DMA) and “Total Muscle Tonus” (TMT) as follows.

1) *Variability of Total Contraction (VTC)*: VTC represents temporal variability of muscle activities. We first calculated amplitude of torque for each muscle using equation (1).

$$|\bar{T}_{Muscle}| = \sqrt{(a_x^{Muscle})^2 + (a_y^{Muscle})^2} \times e_{Muscle}(t) \quad (1)$$

where,  $a_x^{Muscle} (\geq 0)$  and  $a_y^{Muscle} (\geq 0)$  denote the parameters for the musculo-skeletal system of the wrist joint, which convert muscle tension into the X-axis component and the Y-axis component of the wrist joint torque respectively.  $e_{Muscle}(t)$  represents the muscle tension of each muscle.

$$VTC = \frac{\int \left( \sum_{Muscle=1}^4 \left| \frac{d(|\bar{T}_{Muscle}|)}{dt} \right| \right) dt}{t} \quad (2)$$

Then, as described in equation (2), we calculated the instantaneous variability of the torque for the four muscles. Finally, the VTC was calculated by averaging the absolute value of the variation with movement duration  $t$  to normalize it for movement duration.

2) *Directionality of Muscle Activity (DMA)*: DMA was evaluated as the ratio of wrist joint torque to the total muscle torque. We first calculated the wrist joint torque from four muscle activities as follows:

$$|\bar{v}_{EMG}| = \sqrt{(g_x(t))^2 + (g_y(t))^2} \quad (3)$$

where,  $g_x(t)$  and  $g_y(t)$  represent X-axis component and Y-axis component of the wrist joint torque estimated from the four muscle tensions.

$$DMA = \frac{\int \frac{|\bar{v}_{EMG}|}{\sum_{Muscle=1}^4 |\bar{T}_{Muscle}|} dt}{t} \quad (4)$$

Then, as described in equation (4), we calculated the ratio of the wrist joint torque to the sum of the torque of the individual muscles, and finally, the DMA was calculated by averaging the ratio for movement duration  $t$  as a normalization.

3) *Total Muscle Tonus (TMT)*: TMT is the parameter having opposite meaning with above-mentioned DMA, and was calculated by subtracting the ratio of wrist joint torque to the total muscle torque from 1 as follows

$$TMT = 1 - \frac{\int \frac{|\bar{v}_{EMG}|}{\sum_{Muscle=1}^4 |\bar{T}_{Muscle}|} dt}{t} = 1 - DMA \quad (5)$$

### B. Neurological Diseases and Parameters

In order to evaluate usefulness of VTC and TMT, we calculated these parameters for patients with cerebellar atrophy and patients with Parkinson’s disease, as well as for normal control subjects. Fig.3 shows the results for each disease.

The VTC indicates variability of muscle activities. Therefore, if there are a number of abrupt changes in the muscle activities, the VTC gets higher. For instance, in case of cerebellar patients (Fig. 2(b)), muscle activities keep fluctuating intensely due to the cerebellar ataxia. As a result, as shown in Fig. 3(a), VTCs for the cerebellar patients tend to be higher than control subjects with much smoother muscle activities (see Fig. 2(a)). In contrast, VTCs for patients with Parkinson’s disease tend to be smaller due to faint modulation of muscle activities.

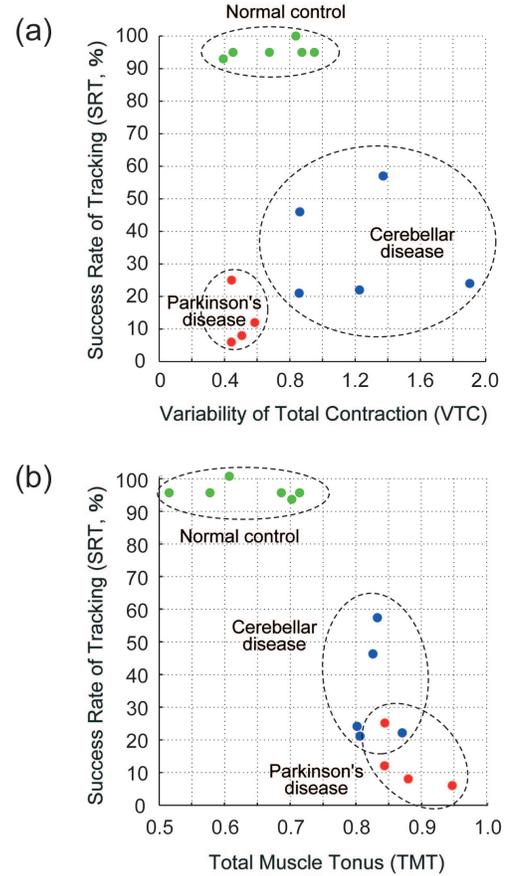


Fig. 3 VTC and TMT for neurological disorders and normal controls. (a) Variability of Total Contraction (VTC). (b) Total Muscle Tonus (TMT). SRT indicates the rate (%) of the cursor within the target for the pursuit movement.

The TMT represents balance component of muscle activities, and thereby indicating contrast between activities of agonist and the antagonist muscles. In other words, as shown in the definition of TMT (equation (5)), TMT is high in case of co-contraction with comparable activities for agonists and antagonists. In contrast, if agonists are activated selectively with complete suppression of antagonists, TMT gets highest. As a result, as shown in Fig. 3(b), TMTs for cerebellar patients and Parkinson’s patients are usually very high due to significant co-contraction (see Fig. 2(b)). On the other hand, in case of control subjects, TMTs are low due to good modulation of agonist activities.

Overall, VTC or TMT captures characteristic patterns of

the muscle activities for patients with cerebellar disorders and patients with Parkinson's disease. Moreover, it is possible to make more detailed characterization of pathological muscle activities by combining these parameters (Fig. 4). If we use more useful parameters in combination with other parameters, it will be possible to make more sophisticated evaluation of movement disorders in a high dimensional space of parameters that quantify patterns of muscle activities. Consequently, it could be possible to evaluate effects of newly developed treatments for neurological diseases in the parameter space.

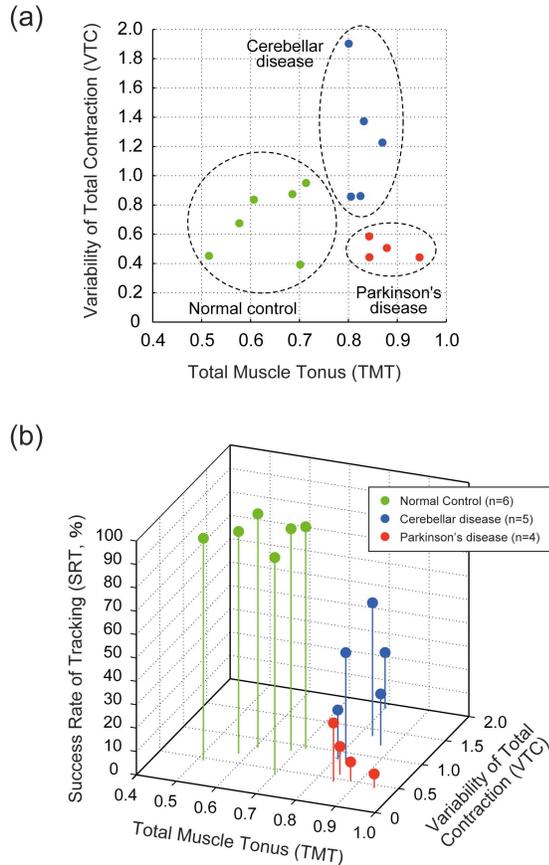


Fig. 4 Comprehensive assessment (a: 2D, b: 3D) of muscle activities for neurological disorders and normal control. Green spheres, blue spheres and red spheres indicate normal controls, cerebellar patients and Parkinson's patients, respectively.

#### IV. DISCUSSION

In this study, we made a quantitative evaluation for the wrist movements. Particularly, based on the EMG signals, we proposed a new method to make a quantitative evaluation for movement disorders from motor commands. In the following discussion, we will focus on two points: 1) How effective our proposed method is; 2) application of our proposed method.

Some researchers tried to make quantitative evaluation of

the motor function for the arm movement [1,2]. For example, by analyzing the position, velocity and acceleration of arm during a circular movement on the digitizer, Nakanishi et al. evaluated the motor function of the arm in patients with neurological disorders including cerebellar deficits and Parkinson's disease. However, their analysis was limited to the movement kinematics. Unfortunately, the movement kinematics cannot specify its causal muscle activities due to the well-known redundancy of the musculo-skeletal system. In other words, completely different sets of muscle activities (causes) end up with the same kinematics (results). Thus, in order to understand central mechanisms for generation of pathological movements, it is essential to capture causal anomaly of the motor commands directly, rather than to observe the resultant movement indirectly [3,4].

For that purpose, we identified abnormal components of agonist selection for wrist movements from muscle activities of the four forearm muscles [5]. For the next step, in the present study, we further extended our analysis to quantify the pathological patterns of muscle activities. Specially, we found two parameters characterizing pathological patterns of the muscle activities. In addition, we found that these parameters, if combined appropriately, are useful to characterize complex patterns of muscle activities for different movement disorders in a way easy to be recognized visually. The high-dimensional parameter space is also useful to evaluate effects of a medical treatment as a shift toward or away from the normal control in the parameter space. It is expected that our proposed methods will be useful for a navigation system of medical treatments or rehabilitation based on the motor commands.

#### REFERENCES

- [1] R. Nakanishi, H. Yamanaga, C. Okumura, N. Murayama, and T. Ideta, "A quantitative analysis of ataxia in the upper limbs," *Clinical neurology*, 1992, pp. 251-258.
- [2] V. Sanguineti et al., "Cerebellar ataxia: Quantitative assessment and cybernetic interpretation," *Hum Mov Sci.*, 2003, pp. 189-205.
- [3] M. Manto, "Pathophysiology of Cerebellar dysmetria: The imbalance between the agonist and the antagonist electromyographic activities," *European Neurology*, 1996, pp. 333-337.
- [4] P. Brown, DM. Corcos, and JC. Rothwell, "Does parkinsonian action tremor contribute to muscle weakness in Parkinson's disease?," *Brain*, 1997, pp. 401-408.
- [5] Jongho Lee, Yasuhiro Kagamihara and Shinji Kakei, "Quantitative Evaluation of Movement Disorders in Neurological Diseases based on EMG Signals", *Conf Proc IEEE Eng Med Biol Soc.*, 2008, pp.181-184.
- [6] M. Haruno and DM. Wolpert, "Optimal control of redundant muscles in step-tracking wrist movements," *J. Neurophysiol.*, 2005, pp.4244-4255. A. Mannard and R. Stein, "Determination of the frequency response of isometric soleus muscle in the cat using random nerve stimulation," *Journal of Physiology*, 1973, pp. 275-296.
- [7] A. Mannard and R. Stein, "Determination of the frequency response of isometric soleus muscle in the cat using random nerve stimulation," *Journal of Physiology*, 1973, pp. 275-296.
- [8] Y. Koike and M. Kawato, "Estimation of dynamic joint torques and trajectory formation from surface electromyography signals using a neural network model," *Biological Cybernetics*, 1995, pp. 291-300.
- [9] H. Beppu, M. Suda and R. Tanaka, "Analysis of cerebellar motor disorders by visually guided elbow tracking movement," *Brain*, 1984, pp.787-809.

# A study on adaptive mechanisms of human gait by means of multidimensional neuroimaging and computational approaches

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**SUMMARY:** To understand the links among the environment, body and brain, we conducted following 5 projects. (1) An fMRI study during imagery and observation of gait elucidated the roles of cortical motor areas in gait planning. (2) A combined gait analysis and blood flow study clarified the pathophysiology of gait disorders in vascular Parkinsonism. (3) A combined fMRI, electromyography (EMG), peripheral nerve stimulation and transcranial magnetic stimulation to the motor cortex allowed us to measure brain activity related to movement generation and proprioceptive afferents. (4) Transcranial direct current stimulation (tDCS) was found to enhance motor functions of the legs. TDCS is now tested for neurorehabilitation of stroke patients. (5) A system was developed for simultaneous measurement of ground force, EMG, electroencephalography, and near-infrared spectroscopy during postural tasks.

## I. INTRODUCTION

Humans employ bipedal gait, which is rather unstable on the earth, for their locomotion. This bipedal locomotor system leads to increased falling tendency especially in elder or diseased population. Falling could cause femoral neck fracture, making many elderly individuals bed-ridden. Moreover, more than a year is required for infants to acquire bipedal locomotion. Because of a long period for locomotor maturation, a chance of survive might be decreased, and a cost for nursing increased. Nevertheless, human beings choose bipedal locomotion through evolution, perhaps to free their upper limbs for manipulating objects, in spite of sacrificing locomotor stability. This capability is believed to compose a building block of human intelligence subserved by the brain, which has brought us to modern civilized society. To understand what the human beings are, it is important to clarify the links between the environment and the body (biomechanics), between the body and the brain (motor control and analysis of somatosensory afferents), and between the brain and the environment (higher brain

functions).

To enhance understanding of the links among those critical factors, the present study aims at contributing to modeling of neural control of gait, by combining measurements of biomechanics and brain activity. The achievement will help to improve robotics, rehabilitation medicine, and development of brain-machine interfaces (BMI). Specifically, we have conducted the following 5 sub-projects between 2006 and 2009.

- (1) In a functional magnetic resonance imaging (fMRI) study, we examined brain activity during observation and imagination of gait movement [1].
- (2) In a combined gait analysis and blood flow study, we examined pathophysiology underlying Parkinson-type gait disturbance in age-related white matter changes [2].
- (3) We developed a simultaneous recoding system of fMRI, surface electromyography (sEMG), and transcranial magnetic stimulation (TMS) [3], and we used this method to discriminate neural activity for generation of movement, and analysis of somatosensory afferents resulting from movement [4].
- (4) In a transcranial direct current stimulation (tDCS) study, we examined if tDCS can enhance muscle activity in the lower extremity [5], and we are trying to find out if tDCS is applicable to neurorehabilitation of gait disturbance.
- (5) We developed a simultaneous recording system of ground force, sEMG, electroencephalogram (EEG) and near-infrared spectroscopy (NIRS) during postural tasks.

## II. BRAIN ACTIVITY DURING IMAGERY AND OBSERVATION OF GAIT MOVEMENT

The purpose of the study was to discover a candidate region of the presumptive cortical gait center that might integrate a variety of gait-related behavior in humans. Functional MRI was used to study the involvement of supraspinal structures in higher-order motor or cognitive gait control. Sixteen right-handed adults were scanned with a 3-T MRI scanner (Siemens Trio) while viewing 8 types of video clips: gait observation, stepping, standing, and “virtual walking”, and 4 different levels of control stimuli. In the gait observation condition, a video clip demonstrated an individual walking normally. Passive viewing of the gait observation stimuli yielded activation of the bilateral motor areas including the supplementary motor areas (SMA) and dorsal premotor areas (PMd). The participants watched visual scenes moving toward them in the virtual walking

This work was in part supported by the Grant-in-Aid for the Priority Areas (“Emergence of adaptive motor function through interaction among body, brain and environment”; area 454) from the Ministry of Education, Science, Sports and Culture of Japan.

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condition where many subjects reported that they felt as if they were walking in the environment. We have previously shown that motor imagery corresponds to planning of movement in the flow of voluntary movement [6]. In consistent, cadence measured during actual walking outside of scanner was significantly correlated with that reported during the virtual walking condition (Figure 1, left panel). In the virtual walking condition, the SMA, PMd, cingulate gyrus, caudate nucleus, thalamus, and midbrain were activated. Common activity in the bilateral PMd and SMA was revealed by a conjunction analysis of the gait observation and virtual walking conditions (Figure 1, right panel).

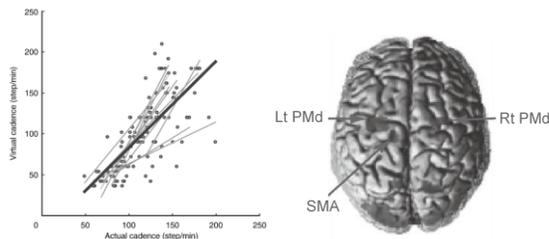


Figure 1: Correlation between cadence during real gait and that during virtual gait (left). Bilateral PMd and SMA were commonly activated during gait observation and virtual walking. Modified from [1].

The present result has supported that the “mirror systems”, which are commonly active during action observation and action generation, may exist for gait movement. The present results also implied that higher-order abstract representations of gait movement might exist in the higher-order motor areas such as the SMA and PMd. The common activity in the SMA and PMd during both gait observation and virtual walking suggests that these areas mediate gait planning of the self and understanding of gait planning of other agents. Understanding of these mechanisms could help development of BMI that assist gait. It is also possible that the dysfunction of the high-order motor areas or isolation of them from the other locomotor regions leads to a neurological syndrome called “gait apraxia”.

### III. PATHOPHYSIOLOGY OF GAIT DISORDERS IN VASCULAR PARKINSONISM

Gait apraxia is considered to result from dysfunctions of high-order motor areas representing planning of gait, but this idea has not been verified yet. We performed a multi-disciplinary imaging study on patients with gait disorders secondary to age-related white matter changes (ARWMC), which reveal mixed hypokinetic and ataxic gait, vascular Parkinsonism, or higher-order gait disorders called gait apraxia. The term of ARWMC has been proposed to describe the neuroradiological state of excessive white matter lesions. Gait disturbance is one of the core symptoms along with cognitive impairment in ARWMC. The pathophysiology of gait disorders in ARWMC patients is

scarcely understood and, above all, the multiple and diffuse nature of the white matter lesions makes it difficult to determine the site of responsible lesions. We addressed this issue by combining a computed gait analysis and cerebral blood flow measurement by means of single photon emission computed tomography (SPECT) [2].

Twenty elderly patients with ARWMC participated in the study. They were classified into 11 gait-disordered (GD) patients and 9 patients with normal gait (non-GD). All the patients underwent a computerized gait analysis (GATAL-ITS-60, Sumitomo Metal Inc. and 9090S, Beltec Inc.) and blood flow activation study with SPECT (Prism 3000, Picker) and  $^{99m}\text{Tc}$ -ethyl cysteinyl dimer.

The GD group showed greater double support time and step width, and slower walking velocity, than the non-GD group. Gait-induced blood flow changes were observed in the SMA, PMd, primary motor (M1) and somatosensory (S1) areas, visual cortex, basal ganglia, and cerebellum. The group comparison revealed underactivation of the SMA, thalamus, and basal ganglia in the GD group. This finding was similar to the one reported in patients with Parkinson’s disease. Moreover, activity in these areas was correlated with variables from the gait analysis; namely, more severely gait disturbed patients had lower brain activity in these areas. Contrarily, right PMd showed overactivity in the GD group than the non-GD group, and this finding suggested that the right PMd might play a compensatory role for restoring gait in the GD group.

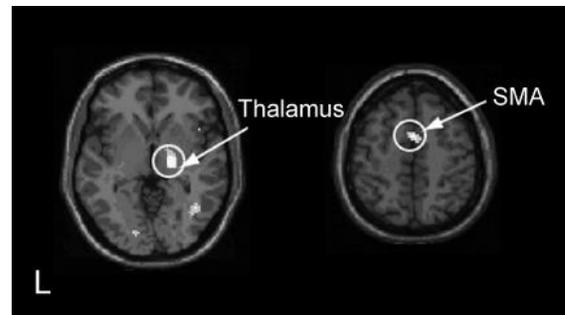


Figure 2: In gait disordered patients with ARWMC, brain activity was decreased in the supplementary motor areas (SMA), right thalamus, and right globus pallidus. Modified from [2].

These results supported functional abnormality in the basal ganglia-thalamo-cortical loops underlying gait disturbance in ARWMC patients. This pathophysiology shares a feature with that reported in Parkinson’s disease [7]. A preliminary analysis of diffusion tensor imaging in ARWMC patients suggests that dysfunction of the basal ganglia circuit is associated with damaged fiber tracts connecting the neural modules (in preparation). Nevertheless, it is difficult to determine if such abnormality causes gait disturbance or results from reduced gait functions. This interpretational issue stems from the fact that brain activity during motor tasks reflects both neural activity for generating movement and activity required for analyzing proprioceptive afferents.

#### IV. SEGREGATION OF BRAIN ACTIVITY FOR MOVEMENT GENERATION AND THAT FOR SENSORY ANALYSIS

Simultaneous measurement of TMS and fMRI is expected to promote understanding of motor control. However, brain activity measured during supra-threshold TMS to the M1 reflects both generation of movement and analysis of proprioceptive afferents as a result from movement. To solve this issue, we developed a method for sEMG recording during a concurrent TMS-fMRI study [3], and then tested if quantified sEMG values could be used for correcting amount of proprioceptive inputs secondary to movement by incorporating a condition with PNS-induced movement [4].

Nineteen healthy volunteers participated in a study at the development stage [3]. An MRI compatible TMS coil was attached to a Magstim Rapid stimulator situated outside of the MRI scanner room. The coil was fixed to the scanner bed with a custom-made device. sEMG was monitored from the right abductor pollicis brevis (APB) (SynAmp, Neuroscan) at a sampling rate of 1 kHz, and motor evoked potentials (MEPs) were recorded. A resting motor threshold (RMT) was determined under MEP monitoring in the MRI room. A 3-T MRI (Siemens Trio) was utilized for acquisition of fMRI data. Twenty single TMS pulses were delivered with the same intensity at a frequency of 0.07-0.125 Hz. Stimulus intensity was varied across fMRI runs at 5 or 10% steps. Mean MEP amplitude was determined for stimulus intensity. FMRI data were analyzed with SPM2 and MATLAB.

We were able to show typical stimulus-response relationship between MEPs and single pulse TMS intensity within the MRI environment. Brain activity evoked by suprathreshold single pulse TMS was observed in motor-related regions including the left M1 (directly stimulated), primary somatosensory cortex, ventral part of the SMA extending into the caudal cingulate zone (SMAv/CCZ), bilateral PMd, second somatosensory cortex, thalamus, and cerebellum as well as in the cognitive/affective regions (Figure 3, left panel). Data from the directly stimulated left M1 and those from the remote SMAv/CCZ are shown in Figure 3 (right panels). Stimulus-response profile

in both regions showed a non-linear component around the RMT. Activity during the supra-threshold stimulation should include activity for analyzing proprioceptive afferents at least in part, but it is not known to what extent proprioceptive afferents contribute to brain activity during motor tasks.

Therefore, we proceeded to a next stage of the study to assess brain activity separately for movement generation and that for sensory analysis, by including a PNS-induced movement condition. Thirty-four healthy volunteers performed voluntary movement in response to TMS clicks and underwent supra-threshold TMS to the M1, and 19 of them also underwent the PNS condition (right median nerve) inducing muscle twitch in the right APB. We recorded sEMG during the experiment (SynAmp, Neuroscan or BrainAmp, Brain Product). FMRI data were analyzed with FSL and SPM5. Distribution of activity did not help to discriminate the effects of proprioceptive afferents from those of movement generation since activity of supra-threshold TMS was overlapped not only with that of voluntary movement but also with that of motor PNS. When quantified sEMG values (mV x ms) were compared between the supra-threshold TMS and PNS conditions, PNS was found to induce greater muscle activity than TMS. The comparison of brain activity standardized with the size of sEMG values clearly showed that supra-threshold TMS induced brain activity that cannot be explained by muscle afferents. The present method will contribute to refining interpretation of brain activity during motor tasks. Additionally, the method will also help to understand the mechanisms of brain stimulation techniques (TMS and tDCS), which are expected to be applied to neurorehabilitation.

#### V. ENHANCEMENT OF LEG MOTOR FUNCTIONS BY TRANSCRANIAL DIRECT CURRENT STIMULATION

TDCS is a non-invasive brain stimulation technique in which weak direct current (~1 mA) is delivered to the brain through the intact scalp and skull. Similar to repetitive TMS techniques, tDCS is reported to modulate brain excitability beneath the electrodes. Previous studies with tDCS have

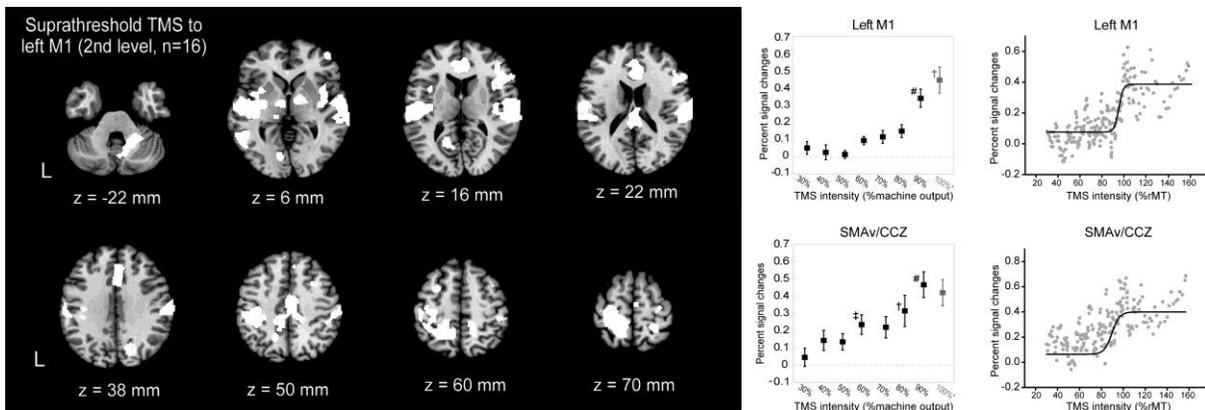


Figure 3: Second-level contrast images between the supra-threshold stimulation and the sub-threshold stimulation. Activity induced by suprathreshold single TMS pulses is observed in the directly stimulated left M1 as well as remote areas including the supplementary motor areas, cingulate motor areas, lateral premotor areas, thalamus, second somatosensory areas, auditory areas and cerebellum. Modified from [3].

shown that tDCS can enhance motor performance of the upper limbs and motor learning. In the present study, we used tDCS to test if it could improve performance of simple motor tasks of the lower limbs in healthy subjects.

Ten healthy volunteers participated in the study after giving written informed consent. They performed motor tasks before, during, and after (30 and 60 min) the application of tDCS to the leg M1. TDCS was delivered for 10 min at intensity of 2 mA. The motor tasks included a pinch force task and a reaction time task. The subjects performed each type of tasks with the left leg and also with the left hand. We employed three stimulus conditions including anode tDCS, cathode tDCS, and sham stimulation. In the sham condition, tDCS was delivered only during the first 10 sec after beginning of tDCS. An interval between successive sessions was about a one week.

The pinch force of the leg was significantly increased during and 30 min after the anodal tDCS in comparison with the baseline force measured before the intervention (Figure 4). This effect was only temporarily observed; the force returned to the baseline level 60 min after the intervention. Neither the cathode tDCS nor the sham stimulation produced statistically significant effects. No effect was observed for the hand pinch force, either. None of the stimulation conditions modulated reaction times in either the leg task or the hand task.

The present study for the first time demonstrated that application of the anodal tDCS to the leg M1 temporarily enhanced strength of the leg muscles. It has been suggested that pinch force of the toes is one of the important factors that influence falling tendency. It may thus be promising to apply tDCS to patients with gait disturbance to see if tDCS is effective in preventing them from falling. We are conducting a study to explore if tDCS could improve leg muscle strength in patients after stroke. Furthermore, we are developing a system to measure changes in brain activity before and after repetitive TMS or tDCS and to understand the mechanism of how brain stimulation could improve motor performance.

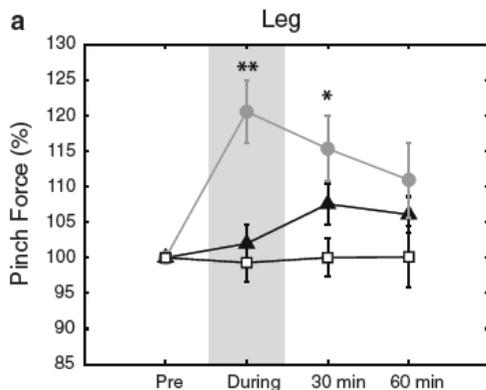


Figure 4 : The effects of tDCS to the leg M1 on pinch force of the toes. Enhancement of the pinch force was observed during and 30 min after the tDCS application. Modified from [5]. \*\* $p < 0.01$ , \* $p < 0.05$

## VI. SIMULTANEOUS MEASUREMENT OF GROUND FORCE, ELECTROMYOGRAPHY AND BRAIN ACTIVITY

We must seek an imaging method with better temporal resolution than now without sacrificing spatial localization ability so as to use information from brain activity during gait or posture to model dynamic changes in kinematics, kinetics and dynamics information. To solve this problem, we have been developing a system combining EEG with high temporal resolution and NIRS with reliable spatial localization during measurement of postural tasks on a force platform.

For measurement of kinetics and dynamics during postural tasks, we combine a force platform with piezoelectric elements (Kistler), 8 channel active EMG amplifiers, and high-speed camera with a sampling rate of 100 Hz. For brain activity measurement, we combine a 24 channel NIRS (FOIRE-3000, Shimazu) and 32 channel active EEG amplifiers (Biosemi). This system will contribute to linking neuroimaging with computational neuroscience of gait and posture.

## VII. FUTURE PERSPECTIVE

The present project yielded knowledge about brain activity for gait planning and execution. Also, technique was developed for segregating between brain activity for movement generation and that for sensory analysis. These outcomes should help to refine information from neuroimaging during gait and posture tasks, and would contribute to developing BMI for posture and gait. We will apply brain stimulation technique tDCS for enhancing recovery from gait/balance disturbance in patients with stroke or Parkinson's disease. Simultaneous measurement of kinetics/dynamics with brain activity will help to understand the mechanisms of brain stimulation technique to enhance neural functions.

## REFERENCES

- [1] K. Iseki, T. Hanakawa, J. Shinozaki, M. Nankaku, H. Fukuyama. "Neural mechanisms involved in observation and imagery of gait movement" *Neuroimage*, vol. 41, no. 3, pp. 1021-1031, July 2008.
- [2] K. Iseki, T. Hanakawa, K. Hashikawa, H. Tomimoto, H. Yamauchi, M. Hallett, H. Fukuyama. "Gait disturbance associated with white matter changes: a gait analysis and blood flow study" *Neuroimage*, vol. 49, no. 2, pp. 1659-1666, Jan 2010.
- [3] T. Hanakawa, T. Mima, R. Matsumoto, M. Abe, M. Inouchi, S. Urayama, K. Anami, M. Honda, H. Fukuyama. "Stimulus-response profile during single-pulse transcranial magnetic stimulation to the primary motor cortex" *Cerebral Cortex*, vol. 19, no. 11, pp. 2605-15, 2009.
- [4] H. Shitara, T. Shinozaki, M. Honda, K. Takagishi, T. Hanakawa. "Understanding of evoked activity in the motor network during suprathreshold transcranial magnetic stimulation to the primary motor cortex" (in submission).
- [5] S. Tanaka, T. Hanakawa, M. Honda, K. Watanabe. "Enhancement of leg motor power by anodal transcranial direct current stimulation" *Exp Brain Res* vol. 196, no. 3, pp. 459-65, Jul 2009.
- [6] T. Hanakawa, M. A. Dimyan, M. Hallett. "Motor planning, imagery and execution: a time-course study with functional MRI" *Cerebral Cortex*, vol. 18, no. 12, pp. 2775-88, 2008.
- [7] T. Hanakawa. "Neuroimaging of standing and walking: Special emphasis on Parkinsonian gait" *Parkinsonism Relat. Disord.*, vol. 12, suppl. 2, pp. S70-S75, October 2006.

# Understanding Social Adaptive Functions

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***Abstract— Animals alter their behavior in order to respond to the demands of changing environments. Society and crowd are one of the dynamic environments. We have investigated the design principle of the mechanisms for social adaptation in animals. We are aiming at constructing a multi-scale model combining our results obtained throughout our studies about the social adaptation mechanisms on various scales.***

## I. INTRODUCTION

ANIMALS acquired the capability to behave adaptively throughout their long history of evolution. In the group C, the main target is social adaptation, especially the mechanisms underlying social adaptive behavior and social structure formation. We consider a society, a population of individuals, as one of the environmental factors that affect animal behaviors, and try to elucidate the mechanisms of social adaptation in various animals. In particular, we focused on the mechanisms underlying expeditious social adaptive behavior and social structure formation. To promote these studies, we have employed two methodologies, “synthetic neuroethology” and “brain-machine hybrid system”. Performances of these models are analyzed, and the adequacies of the models are tested by the behavioral studies using real animals.

Animals have evolved nervous systems to adapt dynamically changing environment. Insects have rather simple and identical nervous systems. Mammalian brain has about  $10^{12}$  neurons. On the other hand, an insect nervous

system has about  $10^6$  neurons. Such insect brains allow us to access each neuron easily, which accelerate us to investigate how animals show socially adaptive behavior from cellular level to behavioral level analysis. The higher functions for social adaptation, such as discrimination and understanding others and the mechanisms underlying impairment of social adjustment have been studied using vertebrates including humans. We are aiming at constructing a multi-scale model combining our results obtained throughout these studies about the social adaptation mechanisms on various scales. We have combined neuroethological approaches and system engineering approaches to understand how animals form social communities, how they learn and retain previous experiences and how they alter their behavior depending on dynamic environments, which will help us to unravel the universal design of central nervous systems.

## II. CONTENTS AND OVERVIEWS

Basic mechanisms underlying social adaptation are investigating using insects. An insect brain consists of only  $10^6$  neurons. In spite of such a small number of neurons, insects have very sophisticated adaptive capability, e.g. higher brain function including learning and sociality. On the other hand, any present robots still do not have such a capability. We believe that the elucidation of the brain mechanism underlying animals’ adaptive behavior is quite useful for establishing adaptive system such as a distributed autonomous system. Complex mechanisms of social formation, such as inter-individual communication, affect or others understanding, are investigating using vertebrates including humans. For example, birds are used for studies on

acquisition mechanisms of social adaptive behavior by vocal communication, Japanese macaques for studies on brain mechanisms underlying the formation of social hierarchy and behavioral decision based on the hierarchy, and humans and machines for studies on others understanding.

In *Synthetic Neuroethology*, enormous independent pieces of physiological knowledge from neurophysiological research are acquired in diverse levels from chemical reaction to cellular and behavioral (individual or social) level. Multiple pieces of the knowledge in multi-levels can be synthesized by technologies in robotics or engineering to derive dynamic system models, which represent the hypotheses of the mechanisms that generate adaptive behaviors. The behavior or performance of the models which should be implemented on simulators or actual robots can be compared with the behavior or performance of the actual living systems, and the models or hypotheses can be verified in ethological manner.

In *Brain-Machine Integrated System*, biology can provide us with biological body components, such as brains, limbs, organs etc. Engineering or robotics can provide us with mechanical body parts, such as sensor devices, actuators, processors, etc. By integrate these body parts; we can construct brain-machine integrated systems, which can also be called *cyborg*. By analyzing the behavior and function of the integrated system, we can investigate the function of the biological components or systems, and can provide robotics scientists with the methodologies to realize artificial systems that can behave adaptively.

We are especially focusing on some specific social behaviors observed in solitary insects, such as crickets and silkworm moths, and the social insects, such as honeybees, ants and termites. Using crickets and silkworm moths, the motivation of behavior, dominant-subordinate hierarchy formation based on the fighting behavior, and the neural mechanisms of courtship behavior have been investigated. The mechanisms of information propagation and sharing within a social group, and the mechanisms of caste formation

and the social order have been investigated using the social insects, especially focusing on the molecular and physiological functions. Moreover, some dynamical models have been constructed based on the biological knowledge obtained throughout these studies, and refined by comparing the simulation results with the biological data. Taking this approach, the adaptation mechanism in insects, as a distributed autonomous system, could be expected to apply into developing a new artificial system. Most vertebrates such as birds and mammals construct and maintain highly organized society based on the individual recognition and inter-individual communication. Affectivity, inter-individual communication, understanding others etc. are very important topics for understanding social adaptive behavior. Songbirds have been used for studying acquisition processes of social adaptive behavior based on the vocal communication, and Japanese monkeys have been used for studying brain mechanisms underlying behavioral decisions based on the social hierarchy. Furthermore, the study of understanding others, one of the important factors of adaptation in the human society, is expected to lead to the elucidation of development process of social adjustment impairments, such as integration disorder syndrome.

Through the research of Group C, we found one of important structure that maintains social adaptive behaviors, that is multiple feedback structure. From modeling of insects' social behaviors that are crickets' aggressive behavior, honeybee dance behavior on collecting food, patrol behavior in ants, and termite caste. These multiple feedback structure is composed of feedback loop in the nervous systems and feedback loop through the social interactions. In the vertebrate animals, similar multiple feedback structure is appeared. Furthermore, feed forward structure would be important to express the social adaptive behavior in humans. We are now carrying on investigating the detail of neuronal function underlying social behavior from cellular level to behavior level.

# Systematic understanding of neuronal mechanisms for real time adaptation in behavior in the changing environment

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**Abstract**— Animals alter their behavior in order to respond to the demands of changing environments. Society and crowding condition are one of the dynamic environments. We have investigated the design principle of neuronal mechanisms for social adaptation in animals, by focusing on how animals determine their behavior depending on previous social interactions or social experiments. Insect pheromone behaviors provide a good model system to elucidate the mechanisms of social adaptation. We have focused on cricket agonistic behavior that is released by cuticle pheromones. We are to reveal behavioral and physiological aspects of socially adaptive behaviors. Nitric oxide (NO) system and octopamine (OA) system in the cricket central nervous system could mediate aggressive behavior of the crickets. Based on our experimental results, we establish dynamic behavior models and neurophysiological models with collaborating engineering group. We are then aiming at constructing a multi-scale model combining our results obtained throughout our studies about the social adaptation mechanisms on various scales.

## I. INTRODUCTION

ANIMALS have evolved central nervous systems to adapt changing environments using long time. The main targets of our researches are underlying social adaptive behavior and the design of the social structure formation. We consider a society as one of the important environmental factors that affect animal behaviors, and try to elucidate the mechanisms of social adaptation in various animals. To promote these studies, we have employed the methodology of “synthetic neuroethology”. Here we construct a dynamical model based on the results of physiological and behavioral experiments. The performances of these models will be analyzed, and the adequacies of the models will be tested by the behavioral studies using real animals.

Insects have rather simple and identical nervous systems than mammalian brain. Thus insects must be good model animals to investigate neuronal mechanisms underlying adaptive behavior. Mammalian brain has about  $10^{12}$  neurons. On the other hand, an insect nervous system has about  $10^6$  neurons. This allows us to access each neuron easily, which accelerate us to investigate how animals show socially adaptive behavior from cellular level to behavioral level analysis. They perceive lots of signals as stimulation from social environment and they adjust their behavior. They do not always respond same way to the same external stimuli. The state of central nervous system must be dependent on their experiences as well as internal and/or external conditions. These factors would mediate threshold of releasing a behavior

or behavioral pattern.

In this study, we have focused on the aggressive behavior of crickets. In order to understand the neuronal mechanisms underlying social adaptation in the aggressive behavior, we have constructed dynamic models for behavior of animals and role of NO/OA system in the brain by collaborating with engineering researchers.

## II. AIMS

The aim of the research is to elucidate the neuronal mechanism of socially adaptive behavior. To understand the mechanisms of social adaptation in Mobiligence, we have focused on neuronal mechanisms underlying social adaptation in insects.

In this study, we have focused on the aggressive behavior of crickets. Most of pheromone-induced behaviors in insects have been thought to be hard-wired: a behavior that could be turn on and off but with no plasticity. However, some of them are revealed to be modified by their previous experiences. Cricket aggressive behavior is an example of such kinds of behaviors. The response of males to the pheromone can be modified by the previous fighting experiences.

## III. ACHIEVEMENTS

In order to understand the Mobiligence in social adaptation, we have focused on cricket aggressive behavior. Insects can adapt to changing environments by emerging adaptive behaviors. We have investigated neuronal mechanisms of behavior decision after fighting between crickets (*Gryllus bimaculatus*). We have performed behavioral experiments, physiological and biochemical experiments to elucidate functional role of neuroactivators such as NO and biogenic amines. We have also performed anatomical research to elucidate information processing pathway in the cricket brain. In order to understand the neuronal mechanisms underlying social adaptive behavior in the crickets, we have constructed dynamic models for behavior of animals and role of NO/OA system in the brain by collaborating with engineering researchers.

### 3-1 Neuronal mechanisms underlying aggressive behavior

Male crickets show intensive aggressive behaviors when they encounter another male (Fig. 1). This aggressive behavior is released by cuticular pheromones. When two males engage in combat, the loser cricket will refuse to fight again. The cricket shows aggressive posture, antennal fencing

to escalate into a fierce struggle. The previous agonistic interactions between male crickets had influence over the following behavior in subordinate males. Once dominant hierarchy was established, the dominant keep aggression if it encountered other crickets whereas subordinate cricket refuse to attack again against the opponent showing avoidance behavior. We have focused on subordinate crickets to understand how animals alter their behavior dependent on social interaction<sup>(1)</sup>. The cuticular pheromones that introduce aggressive behavior have not identified. Collaborating with Prof. Yamaoka, we identified the nature of the cuticular substances. We then performed anatomical research to elucidate the circuits of cricket brain. The neuronal processing pass ways for the information of cuticular pheromones was investigated. The antennal lobe is the primary center for the chemical processing. It is composed of 49 glomeruli. The tactile signals, on the other hand, are processed at ventral area of flagellar afferents (VFA). The innervation of the projection neurons from AL or VFA was stained using fluorescent dyes. We found that the tracts from the AL and the VFA shared several projection tracts, but their termination areas were segregated in the lateral protocerebrum<sup>(2)</sup>.



Fig. 1. Fighting between male crickets.

### 3-2 Multimodal inputs mediating aggressive behavior

Then we investigated the neural mechanism underlying fighting behavior. We here examined the effects of antennae information and of visual information on aggressive behavior. In order to examine if antennae are necessary to release aggressive behavior in males, the behavior responding to the other male were observed 1 hr after antennal legions. Over 90 % of intact crickets showed aggressive behavior, such as antennal fencing and/or threat posture, and start to fight with the other male. On the other hand, the percentage of aggressive crickets was significantly reduced when the whole antennae were cut. These results suggest that the male crickets use the sensory information from the antennae to perform correctly to other crickets, i.e. the aggressive behavior to males or the courtship behavior to females<sup>(3)</sup>.

Although the males whose antennae were removed did not show clear aggressiveness against other males that neither have antennae, they could fight against other intact male. When they faced to the intact male, the percentage of the aggressive males got significantly higher than that to the males without the antennae. The level of the fighting between the intact male and the male without the antennae was not significantly different compared with those between intact

males. These results suggest that the inputs from the antennae are necessary to start fighting to other males. The fact that the males without the antennae could fight against the intact males under the dark conditions suggesting that there could be at least two parallel pathways to elicit aggressive behavior, 1) one mediated by the sensory input from the antennae, and 2) the other one mediated by the mechanical input from the body surface. In order to examine the effects of visual cue on releasing aggressive behavior in male crickets, compound eyes were painted with enamel or behavior experiments were performed under red light. Interestingly, the duration of fighting increased significantly if visual cue was blocked. Cricket fighting is terminated if one of male give up continues attack and escape from the opponent. If their visual cue were blocked, they might not notice if opponent recognize lose each other. Then they would continue fighting. Using these results of behavior experiments, we collaborate with Ota's group to build a dynamic model explaining the effects of multi modal information on releasing aggressive behavior.

### 3-3 Functional role of NO/cGMP signaling on aggressive behavior

Pharmacological and behavioral experiments demonstrated that nitric oxide (NO) signaling system mediates aggressive behavior in male crickets and formation of social hierarchy. It is also demonstrated that the biogenic amine level in hemolymph mediates cricket aggression<sup>(4)</sup>. Our previous work indicated cuticular pheromones increase NO releasing at the antennal lobe in the cricket brain. Histochemical analysis showed that the distribution of putative NO releasing neurons and octopaminergic neurons overlapped in similar region of the brain. We then hypothesize that NO/cGMP system mediate Octopamine (OA) system in the cricket brain. NO and biogenic amines could work as neuromodulators in the nervous systems, which would mediate behavioral selection in the brain.

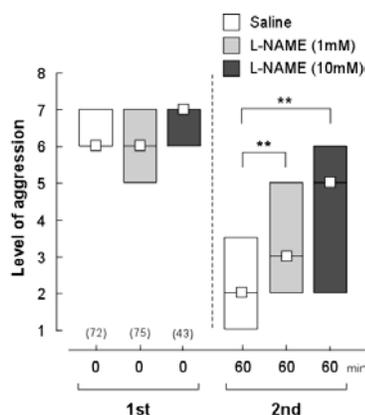


Fig. 2. The effects of NOS inhibitor L-NAME on the aggressive behavior.

Effect of NO/cGMP signaling on aggressive behavior has been examined by pharmacological and behavioral experiment. Inhibition of NO/cGMP signaling pathways impaired the behavioral selection in subordinates, and thus it is suggested that the NO/cGMP signaling plays a crucial role

in the behavioral decision. The behavior of subordinate whose antennae were removed was interestingly similar to the behavior of subordinates whose NO/cGMP signaling was inhibited. This suggests that NO/cGMP signaling in the antennal sensory information-processing pathway could participate with the neuronal mechanism underlying aggressive behavior.

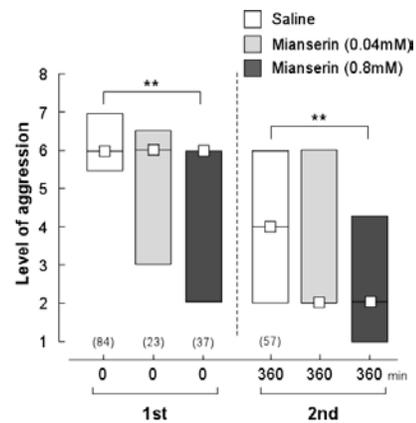
### 3-4 Time window of NO modulation in the aggressive behavior

In order to examine the effective timing of NO/cGMP signaling on introduce adaptive behavior, we performed pharmacological experiment. NO is generated by activating NOS and diffuses about 100  $\mu\text{m}/\text{sec}$  through cell membrane of the target cells. It activates soluble guanylyl cyclase to increase cGMP level. The functional concentration of NO is thought to be 10-100 nM in the nervous system<sup>(5)</sup>. The lifetime of NO in the tissue is very short. These natures of NO suggest that effective time window must be necessary. Here, we inhibited the activity of NO synthase (NOS) using a specific inhibitor L-NAME. L-NAME was injected into the brain of the cricket prior to the first engagement. Twenty min after the head injection of L-NAME, 2 males were placed in the arena to encounter each other. There are no significant changes between control pairs and L-NAME injected pairs in the first encounter. After fighting was settled, they were kept isolated for 60 min and then behavior of subordinates as the second encounter was observed. The losers became more aggressive than control animals (Fig. 2). However, if L-NAME is injected into the brain of loser crickets after first fighting was settled, most of losers avoided fighting soon after they notice opponents in the second encounter. There is no significance between control and L-NAME injected losers. Our previous results indicate that NO decreases biogenic amines in the cricket brain. These results indicate that it is necessary for losers to generate NO in the brain before or during the first encounter to mediate avoidance behavior in future encounter with other crickets. Thus, the timing of NO release and timing of decrease of biogenic amine must be also important factor.

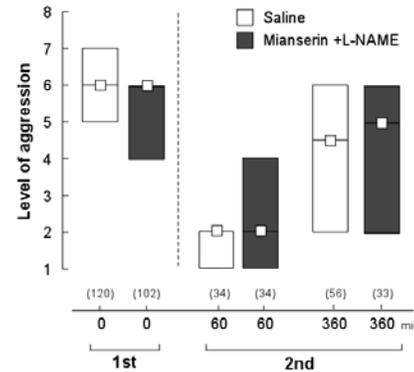
### 3-4 Effect of octopamine on aggressive behavior

We observed the aggressive behavior after injection of the OA antagonists, mianserin or epinastine, so that we can examine the role of OA signaling in aggressive behavior. The antagonist solution was injected 60 minutes before the first encounter, and the second encounter was made 360 minutes after the first encounter. In the first encounter, both mianserin- and epinastine-injected groups showed significantly lower aggressive levels compared with those of the control group (Fig. 3). In the second encounter, only the mianserin-injected group showed significantly lower aggressive behavior than those of the control group. These results suggest that injection of the OA antagonist causes the slower recovery of the aggressive behavior of the cricket. Similar with the case of L-NAME injection, the effect of the mianserin injection was also dose-dependent. Injection of the higher concentration of mianserin induced much lower aggressive levels both in the

first and the second encounters.



**Fig. 3.** Levels of aggression of male crickets in the first and the second encounter after the injection of the octopamine antagonist, mianserin. Saline or mianserin was injected into the head before the first encounter. The second encounter was made 360 minutes after the first encounter.



**Fig. 4.** Levels of aggression of male crickets in the 1st and the 2nd encounter after the injection of L-NAME and mianserin. Saline (white) or L-NAME & mianserin (dark gray) was injected into the head before the first encounter.

The results of L-NAME and mianserin injection suggest that the NO and OA signals have mutually opposite physiological effects on aggressive behavior in the cricket, i.e. NO has an inhibitory effect whereas OA has a facilitating one. To confirm if the effect of NO is countered by OA and vice versa, we tried to inject the mixture solution of L-NAME and mianserin. The mixture solution was injected 60 minutes before the first encounter, and the second encounter was made 60 or 360 minutes after the first encounter. In the first encounter, the level of aggression of the mixture-injected group was not significantly different with those of the control group (Fig. 4). The mixture-injected group showed significantly higher aggressive levels compared with the control group. However, they are significantly lower than those of the 10 mM L-NAME-injected group. In the second encounter with 360 minutes interval, the aggressive levels of the mixture-injected group were not significantly different with those of the control group, whereas they were significantly higher than those of the 0.8 mM mianserin-injected group. These results clearly showed that

L-NAME and mianserin were not effective to the aggressive behavior of the cricket when they were injected together.

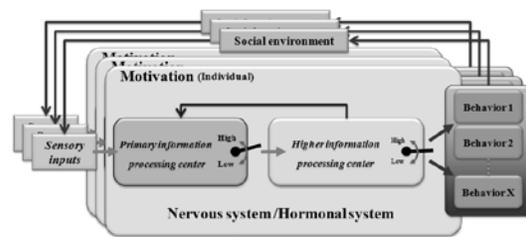
We demonstrated that the NO and OA signals modulate the experience-dependent aggressive behavior of male crickets. The behavioral change in the subordinates recovered fast when the NO signal was inhibited, whereas it recovered slowly when the OA signal was inhibited. How the NO signal involves in the aggressive behavior of the cricket? It has been reported that the NO is one of the neuromodulators controlling animals' aggression in vertebrates [7]. It could be possible that the NO signaling directly control releasing an aggressive behaviour also in the cricket. One the other hand, NO is also well known as a neuromodulator that play an important role in olfactory information processing both in vertebrates and invertebrates<sup>(6)</sup>. Also in crickets, both NO generating and target neurons are distributed in the olfactory system in the brain, including the antennal lobe and the mushroom body<sup>(7)</sup>. It is believed that the aggressive behavior of the crickets was elicited by detecting male cuticular substances by the antennae. Furthermore, we recently found that the antennal stimulation of the male cricket by a male forewing caused NO gas generation in the antennal lobe. Taken these observations together, it could also be possible that the antennal information processing of the cuticular substances was disturbed by inhibition of the NO signal, and the aggressive behavior was modulated. In the cricket, it has been suggested that OA represents a motivational component of aggression<sup>(8)</sup>. Recently, our group found that the OA level in the brain was modulated by the NO signal, suggesting that the NO signal was somehow linked to the OA signal in the CNS. The fact that the OA antagonists abolished the effect of NO blockade on aggressive behavior is strongly support this idea. At present, the signaling cascade between NO and OA is hardly studied, and a total understanding of NO and OA system is necessary to get deeper insight on the neural mechanisms of aggressive behavior in the cricket. Considering this point, a systematic study using simulation technique based on the biological data must bring us a breakthrough.

#### IV. CONCLUSION

We have investigated neuronal mechanisms underlying behavior selection dependent on fighting experience in the crickets. We have focused on role of NO signaling and OA system in the brain. Based on our results, we constructed dynamic behavior models and neurophysiology model with engineering research groups. The behavior model demonstrated cricket behavior dependent on population density. The model proposed here has been refined by comparing the simulation results and the biological experiment data. In order to examine the simulation of this model, we removed dominant agent from the group of artificial crickets. Then measured how long it takes to reconstruct dominance relationship and found that it was less than 10 min. Then we tried the same experiments using animals. We placed several males in the arena. Crickets usually start fighting and one of them becomes a dominant.

Then we remove the dominant from the group and observed the behavior of rest crickets. One of subordinate crickets becomes dominant if dominant animal is disappeared. Interestingly, it was also within 10 min. This indicates that internal state is modified by individual interactions among crickets. Neurophysiology model was also constructed to demonstrate that multiple feedback structure is necessary to explain cricket behavior. The behavior model and cricket behavior experiments also demonstrated that social interactions improve internal state of animals.

Through our research, we have found one of important structure that maintains social adaptive behaviors is multiple feedback structure is composed of feedback loop in the nervous systems and feedback loop through the social interactions.



**Fig. 5.** Multi-feedback structure for adaptive social behavior. Feedback loops appeared in the nervous systems and through social environment is most important mechanism for real time adaptation in the social environment.

#### V. REFERENCES

1. Aonuma H, Nagao T, Ota J, Kawabata K, Asama H (2007) Modeling of socially adaptive behavior and its application – Lesson from agonistic behavior in the cricket–. *J. Socie. Instr. Contr. Engin.* 46: 903-909.
2. Yoritsune A and Aonuma H (2007) 3-D atlas of the cricket antennal lobe. *Proc. International Symp. Mobiligence*, 2: 187-190
3. Sakura M, Yoritsune A, and Aonuma H (2007) Fighting experiences modulate aggressive and avoidance behaviors in crickets against male cuticular substances. *Proc. International Symp. Mobiligence*, 2: 243-246
4. Stevenson PA, Hoffmann HA, Schoch K, Schildberger K (2000) The fight and flight responses of crickets depleted of biogenic amines. *J Neurobiol* 43: 107-120
5. Aonuma H., Kitamura Y., Niwa K., Ogawa H. and Oka K. (2008) Nitric oxide-cGMP signaling in the local circuit of the cricket abdominal nervous system. *Neuroscience*.157: 749-761.
6. Breer H, Shepherd GM (1993) Implications of the NO/cGMP system for olfaction. *Trends Neurosci* 16: 5-9
7. Aonuma H, Niwa K (2004) Nitric oxide regulates the levels of cGMP accumulation in the cricket brain. *Act Biol Hung* 55: 65-70
8. Stevenson PA, Dyakonova V, Rillich J, Schildberger K (2005) Octopamine and experience-dependent modulation of aggression in crickets. *J Neurosci* 25: 1431-1441

# Modeling of Fighting Behavior in Crickets

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Abstract: Individual interaction among crickets was simulated by constructing an artificial cricket model. Using simulations of artificial cricket models with multi-layers, we investigated the principle mechanism underlying social interaction.

Keywords: multi-agent robot systems, crickets, adaptive behavior

## 1. Introduction

Our group studies adaptation mechanisms of crickets to other individuals and environments, through analyzing fighting behaviors among crickets and the effect of social population.

Our aim is to clarify the mechanisms embedded in animates to adapt to other animates and environments. In our study, we apply a system engineering approach with mathematical models focusing on the crickets to clarify its mechanisms of adaptation. This can be basis of the social adaptive mechanism of animates. The cricket models are created with multiple layers such as a neuronal structure level, an individual behavior level, and group behavior level.

In Chapter 2, behavior modeling of crickets is presented connecting cricket individual fighting behavior and the effect of social population. In Chapter 3, it is discussed that simulated swarm behavior based on proposed neuronal circuit model of the cricket and advanced modeling approaches. In Chapter 4, growth modeling of cricket is described considering growing environment. We conclude the paper in Chapter 5.

## 2. Behavior modeling of crickets

Insects provide good model systems to investigate neuronal mechanism underlying adaptive behavior.



Fig. 1 Fighting behavior of male crickets

Cricket agonistic behavior must be a good model system to understand the mechanism of social status formation. (Fig. 1).

The question of whether crickets are able to recognize one another to establish social status in an agonist interaction is worthy of pursuit. We examined the social organization among male crickets with the experiments involving a behavior experiment using real animals. Our results suggest that crickets establish social status without recognition of their opponents. (Fig.2) [1].

Aggressive behavior of male cricket is released by cuticular substances on the body surface of male cricket and the aggression levels escalate until one of male crickets evacuate from the fighting. This is occurred in the cricket's brain. The model was constructed by observation of cricket behaviors in a population and probability P of a behavior pattern was given where P is dependent on a component of time decay and memory which we determine as  $\alpha$  (Fig. 3). Using the simulator we examine the effect of social population on the cricket's behaviors (Fig. 4). When the population of cricket was low density, fighting behavior showed rather random

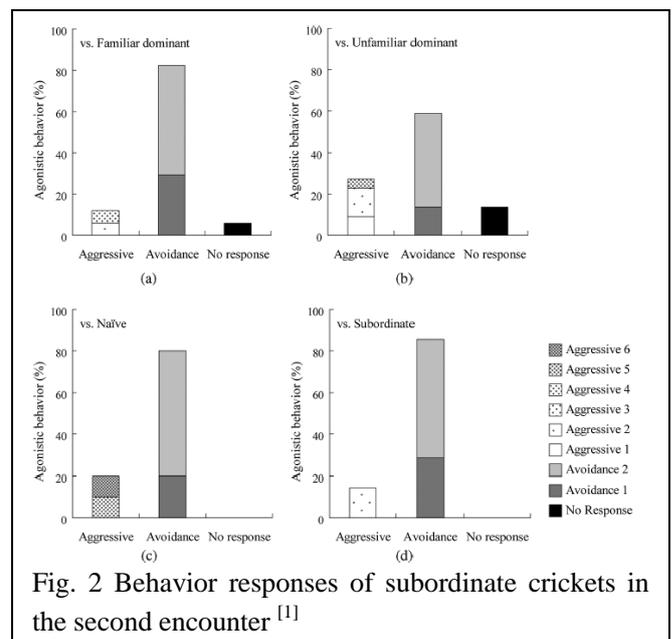


Fig. 2 Behavior responses of subordinate crickets in the second encounter [1]

pattern. When the population was middle density, only one of crickets did beat other crickets to keep dominant status. When the population was high density, almost all crickets always moved to avoid interaction. The proposed model could simulate mechanisms underlying social behavior in insects and that in turn must help us to understand neuronal mechanisms underlying adaptive behaviors [2].

We have proposed an algorithm for multiple mobile robots performing a foraging task. In the proposed algorithm, robots select behaviors based on their activities, which were adjusted by interaction with other robots and foods. The proposed algorithm was inspired by the mechanism governing the fighting behavior in male crickets. Simulation results showed that the algorithm is

efficient in a dynamic environment [3].

We have also investigated the effects of I/O relation on releasing aggressive behavior by using handicapped crickets whose visual inputs or antennal inputs are artificially disabled [4] (Fig. 5) .

### 3. Neuronal Circuit Modeling of Cricket

The purpose of this study is to construct a dynamic neuronal circuit model of cricket based on the biological knowledge related to cricket fighting behavior. We named this approach “Synthetic Neuroethology” and were discussing to compare simulation results using our model with actual cricket’s behavioral knowledge.

#### 3.1 NO/cGMP-OA model for individual behavior modification

We focused on the modification of behavior selection of the cricket based on its experience. Our model consists of a diffusion equation for NO(Nitric Oxide) concentration, differential equations for cGMP(cyclic GMP) and OA(Octopamine) concentrations and a threshold model for behavior selection utilizing OA concentration (Fig. 6).

Computer simulation results show that our proposed dynamic model can express individual behavior modification based on experience.

#### 3.2 Extended NO/cGMP-OA model for both of individual and group behavior modification

Since simulation results related to multi-individual environment by using NO/cGMP-OA model could not explain the group behavior modification based on the population density. Therefore, we attempt to extend the model based on both of knowledge related to biogenic amine effect and the hypothesis related to contact frequency effect (Fig. 7).

In this model, when the cricket detects the other male’s pheromone, Efficacy of the pheromone stimulation works as a threshold value for OA concentration. Here, Efficacy value means the signal propagation efficiency of primary sensory processing center. After the cricket contacts with another male, if OA value is over Efficacy, the cricket can take aggressive behavior and if it is not, the cricket shows no response to the stimulation. During the aggressive behavior, the cricket selects avoidance behavior when the OA value is under Efficacy value.

In extended model, OA value is also adjusted by NO/cGMP-OA model and Efficacy (E) is modified as follows. The winning experience after selecting aggressive behavior make the value of E decrease certain quantity. When the cricket is defeated, the value of E

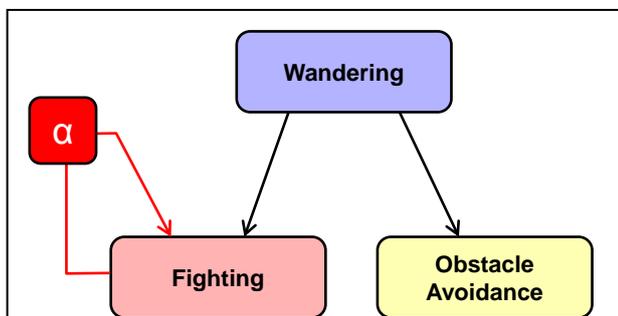
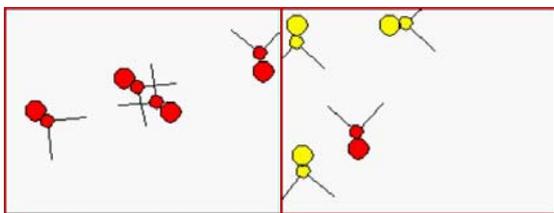


Fig. 3 Behavior Model of Crickets



(a) initial state (b) final state

Fig. 4 Example of simulation results

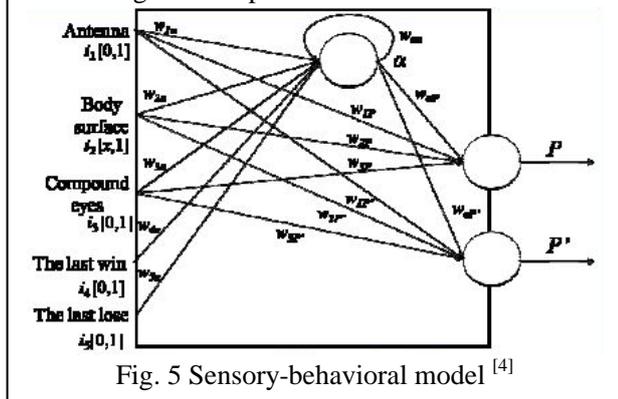


Fig. 5 Sensory-behavioral model [4]

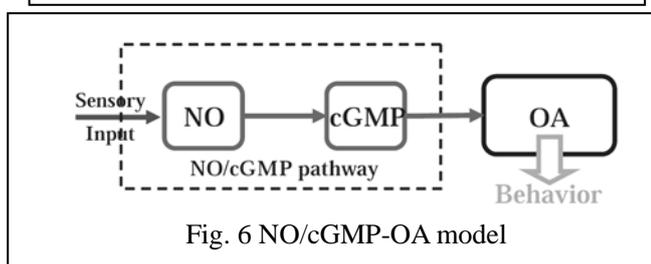


Fig. 6 NO/cGMP-OA model

shows an increase of certain quantity. Also, the dynamics of recovering Efficacy is expressed as equation (1).

$$E = A \times 10^{\alpha t} + B + g(F_{in}) \tag{1}$$

where A, B and  $\alpha$  indicate the constant respectively and t indicated time after fighting. This equation consists of time effect dynamics for memorizing its experience and also the effect by the contact with the others. The effect from the contacts with others is expressed as equation (2).

$$g(F_{in}) = -\beta \times F_{in} \tag{2}$$

$$F_{in} = \begin{cases} 1 & \text{contact with another one} \\ 0 & \text{otherwise} \end{cases}$$

where  $\beta$  indicates inhibition influence and  $F_{in}$  means existence of the contact.

In extended model, OA value and Efficacy are referred to determine to select the behavior. From the results of computer simulation using this model, individual behavior modification like the one by NO/cGMP-OA model is shown. Moreover, the simulation results of group behavior (4 agents, field size adjusted) is shown in Fig. 8.

Here, when it is set as  $\beta = 0.005$ , the group behavior modification appears similar one of the real cricket's group behavior. As the result, this model is an adequate one which explains both of individual and group behavior.

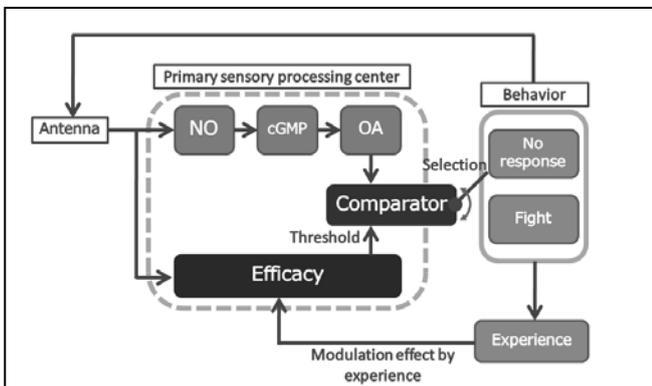


Fig. 7 Extended NO/cGMP-OA model with efficacy effect

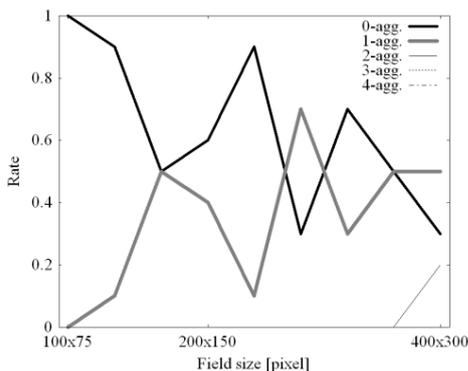


Fig. 8 Simulation result

Moreover, Efficacy adjustment factor with biogenic amine effect and the effect of the contact with others gives any effects to group behavior modification. Thus, it is expected that the efficacy dynamics takes important role for cricket's behavior selection in the fighting behavior.

#### 4. Growth Modeling of Cricket

It has been reported that many of vertebrate and invertebrate species show overdevelopment of aggressive behavior increased by social isolation: human is no exception. The study of this has been done with a few vertebrates: rat, mouse, monkey and so on. On the other hand, studies with invertebrates have benefits that nerve system of invertebrates is simple and has a little individual difference. And there are two invertebrate which shows such overdevelopment: cricket and fruit fly. We use cricket for its larger body size to elucidate the cause of that overdevelopment. Study with cricket would be contributory to elucidate the interspecific nerve system of aggression.

Aggressive behavior is modulated by an amount of octopamine (OA) and serotonin (5-HT) in the brain. There are a lot of studies about that but they are just fragmentary information. So we constructed a neuronal model from these fragmentary studies (Fig. 9).

There are several types of serotonin neuron and its receptor. There exists an argument whether serotonin system has a negative feedback (autoreceptor) or not to modulate aggressiveness (Fig.10). So, we firstly constructed two models with differential equation: the model with negative feedback and the model without negative feedback. Next, we confirmed that large amount of 5-HT in the brain drives crickets to start fighting with pilot study by pharmacological experiment. And it is reported that 5-HT in the brain decreases when cricket loses. So we assumed that recovery speed of serotonin expresses forgetting rate. We compared forgetting curve between two 5-HT models and experimental data, and concluded to adopt the model which considers negative feedback (Fig. 11)<sup>[5]</sup>. We constructed OA model without negative feedback.

Next we took a multi-agent simulation with this internal model. The parameters, time-constant of 5-HT and so on, are determined by past biological studies. The tendency for crickets to start fighting increases with increased amount of 5-HT and OA, and we construct a parameter called toughness which increases when OA and 5-HT increase. We use this toughness for

constructing the probability of pairing (Fig. 12). Finally, probability of pairing is determined to be multiplied the density of space as shown Fig. 13, and we observed the transition of 5-HT auto-receptor with changing the density of space. We found that there exists a bifurcation phenomenon about crickets' autoreceptor and that mean value of autoreceptor in crickets' group monotonously decreases. Toughness  $F$  increases with larger autoreceptor (Fig. 14) [6]. These results explain experimental fact about overdevelopment, so we constructed the cricket's internal model under the approach of empirically constructivism.

## 5. Conclusion

Cricket models are created with various layers. Simulation results indicate the effectiveness of the proposed models. Future studies will deal with thorough collaboration with biological studies.

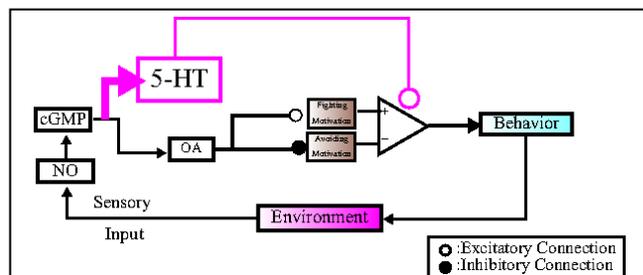


Fig. 9 Behavior is determined by an amount of Octopamine (OA). Behavior is neuro-modulated by an amount of serotonin (5-HT).

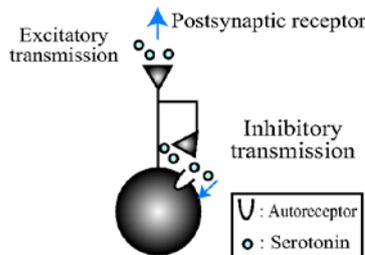


Fig. 10 Inhibitory effect caused by autoreceptor-like negative feedback [6]

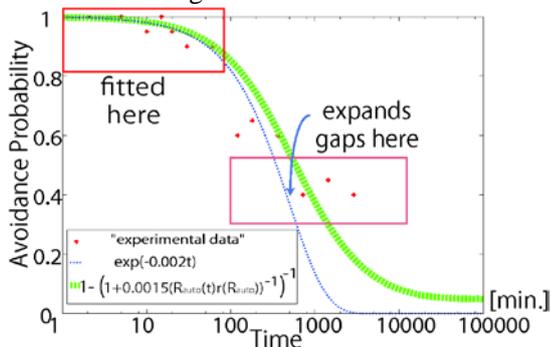


Fig. 11 It shows forgetting curves derived by the model with negative feedback (green), and the model without negative feedback (blue), and experimental data (discrete point).

## References

- [1] Masatoshi Ashikaga, Midori Sakura, Mika Kikuchi, Tetsutaro Hiraguchi, Ryosuke Chiba, Hitoshi Aonuma, Jun Ota, Establishment of Social Status without Individual Discrimination in the Cricket, *Advanced Robotics*, 23, 5, 563/578 (2009).
- [2] Masatoshi Ashikaga, Modeling of the Mechanism underlying Agonistic Behavior in the Cricket, Ph.D Thesis, The University of Tokyo, (2009), in Japanese.
- [3] Masatoshi Ashikaga, Mika Kikuchi, Tetsutaro Hiraguchi, Midori Sakura, Hitoshi Aonuma and Jun Ota: Foraging Task of Multiple Mobile Robots in a Dynamic Environment Using Adaptive Behavior in Crickets, *Journal of Robotics and Mechatronics*, 19, 4, 466/473 (2007).
- [4] Tatsuya Mizuno, Midori Sakura, Masatoshi Ashikaga, Hitoshi Aonuma, Ryosuke Chiba and Jun Ota, Modeling of the Effects of Multi-modal Inputs on the Aggressive Behavior using Handicapped Crickets, *Proc. 3rd International Symposium on Mobiligence*, 332-337 (2009).
- [5] S. Yano. et al., Forgetting curve derived by serotonin hypothesis in Cricket, *Gryllus Bimaculatus*, *Mobiligence in Awaji*, (2009).
- [6] S. Yano, et al., Development of Neurotransmitter Modulation on Aggression and Dominance Hierarchy in Cricket, *Gryllus Bimaculatus*, *SICE2009*, (2009).

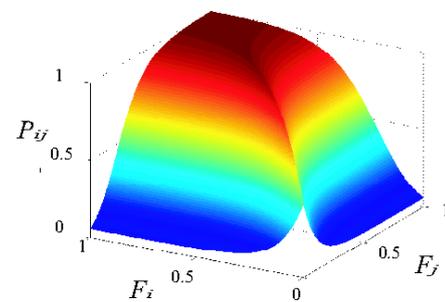


Fig. 12 It shows a probability of pairing between cricket  $i$  and  $j$ . Toughness of them ( $i$ . d.  $F_i$  and  $F_j$ ) is determined by an amount of OA and 5-HT.

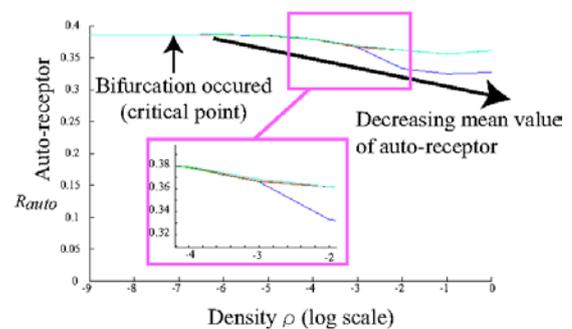


Fig. 13 Relation between spatial density  $\rho$  and an amount of auto-receptor. High density produces low auto-receptor.

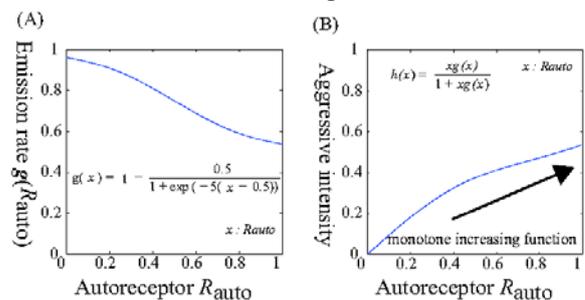


Fig. 14 Large amount of auto-receptor causes high aggressiveness.

# Adaptive behaviors emerged by functional structures in interaction networks

C01-03 Daisuke Kurabayashi Ryohei Kanzaki

**Abstract**— Insects have only a little brain but the behavior is highly adaptive. We consider that physical structure of the interaction network works on the creation of the brain function and model the behavioral processor that controlled by its structural disposition. In this research, we investigate mechanisms for intelligent behaviors through novel approach called bio-machine hybrid systems. We focus on (i) insect-driven robot to see adaptabilities, (ii) cyborg contained by insect-brain and mechanical body, and (iii) network property to expose long-lasting excitation.

**Key Words:** Bio-machine hybrid system, network, *bombyx mori*

## 1 Introduction

In this study, we investigate adaptive behavior switching mechanism.

A moving individual obtains many types of information through interactions with other individuals and environments. Creatures can behave adaptively according to dynamical body and environment, although robots, artificial products can work perfectly only in limited environment. Insects have high adaptability with limited resources. So, we have focused on the aspect of network property in some levels observed in creatures.

In our research project, we try to make the difference clear between artificial intelligence (AI) and a living brain. By using same body and environment, we can observe the difference. This will make possible to build novel network model to exhibit adaptability like a silkworm moth does.

We consider that a physical structure of the interaction network plays quite important roles on the creation of adaptive functionality. In this research, we investigate mechanisms for intelligent behaviors through novel approach called bio-machine hybrid systems. We focus on (i) insect-driven robot to see adaptabilities, (ii) cyborg contained by insect-brain and mechanical body, and (iii) network property to expose long-lasting excitations.

In this study, we focus on a small insect, silkworm moth *Bombyx mori*. A female moth distributes special chemicals, called pheromones. A male moth moves toward to the female by sensing the pheromones. For the purpose, it makes a typical sequential motion: straight, zigzag, and turn<sup>1)-3)</sup>.

## 2 Adaptability exposed by insect-controlled robot

In this section, we describe an experiment system by which we can observe walking motion of a silkworm moth directly and we can manipulate correspondence between actual motion and walking pattern. The ex-

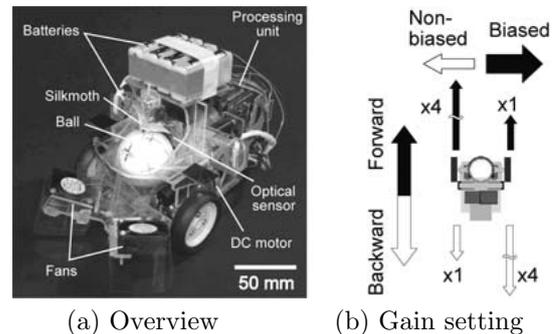


Fig. 1: Experimental setup of insect-controlled robot.

perimental system, named “insect-controlled robot”, is composed of walking monitoring system with a living silkworm moth and robot body with two driving wheels. We have already analyzed adaptability of a silkworm moth against manipulation of gains to drive motors, and discovered importance of visual inputs for adaptability. We have also made analysis of adaptability against time lag (delay) to drive motors on the robot body, and then consider about fusion system of odor and visual inputs.

An “insect-controlled robot<sup>4)</sup>” is a robot that a silkworm moth drives. By changing control parameters of the robot, we can estimate adaptability of a silkworm moth. In this section, we describe research results of visual effects and servoing performance to reach at a pheromone source.

### 2.1 Arrangement of the program behavior by optic flow

Figure 1(a) shows the developed insect-controlled robot. A silkworm moth, tethered on its back, walks on a ball. A light sensor reads movements of the ball, then a microcomputer on the robot body translates movements of the moth into motion commands for electric motors. Therefore, robot body moves just like a moth does.

We have investigated performance of reaching behavior under unusual driving gains. As Fig. 1(b), we

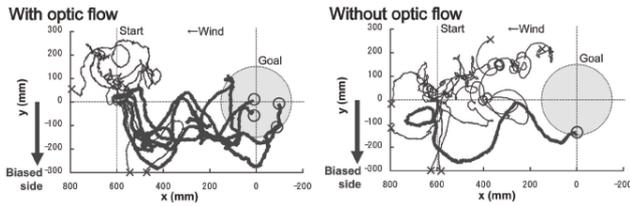


Fig. 2: Trajectories of the manipulated robot with (left) and without optic flow (right).

changed the driving gain of the left motor 4 times faster than that of the right one. We have compared behaviors of the insect-controlled robot with and without visual input. Most of insects detect optic flow and arrange its trajectory according to optomotor response. However, because the effect of mating pheromone is too strong, we hardly observe the effect of visual input on a silkworm. In this project, we attach transparent or white shield in the front of insect-controlled robot to give or not to give visual information. We set a insect-controlled robot in a wind tunnel (1800(L) x 900(W) x 300 mm(H)) 60cm away from a pheromone source, then observed its trajectory.

Figure 2 shows the trajectories. When we give optical information, we have 11 arrivals in 14 trials. However, we have only 4 in 14 without optical input. Additionally, when we suddenly change a driving gain during an experiment, a silkworm arranges its motion within 1[s]. Thus, we can conclude that a silkworm utilizes optic flow and arrange its action by optomotor response.

## 2.2 Response against time delay

In a dynamic environment, a creature must be adaptive. An insect has both optomotor response and program behavior exhibited by chemicals. We have investigated difference of time delay between the two. We inserted a certain time delay (0-1000[ms]) before driving electric motors, then carried out experiments to reach at a pheromone source. We also apply uneven driving gains in order to evaluate speed of behavior arrangement through optic flow. We employed 10 insects for each condition.

Figure 3 illustrates the success ratio to the time delay. When the robot has equal driving gain (1:1), the success ratio was very high, for example, even if we set 600 [ms] delay, it was 80%, and when we set 1000 [ms] delay, 50% trials achieved the goal. In the contrast, when the robot has uneven driving gain (1:4), the success ratio significantly decreases, for example, only 50% success to 400 [ms] delay.

When the driving gain is balanced (1:1), the behavior of a silkworm moth is quite robust against time delay. This result suggests that real-time feedback is not so important to achieve pheromone source. Because pheromone molecule forms plumes, it is quite difficult to follow density of pheromone in the atmosphere

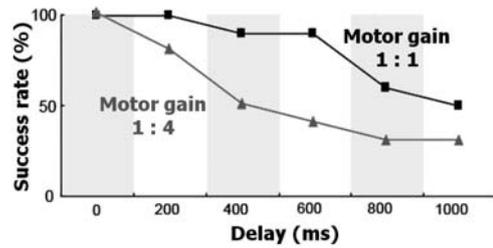


Fig. 3: Relationship between success rate of localization and delay of motor control of the robot.

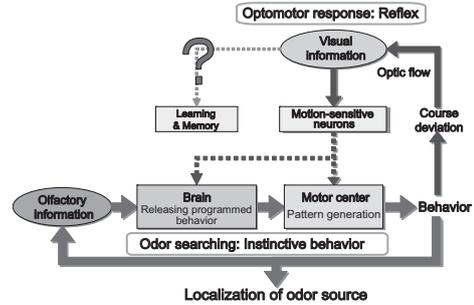


Fig. 4: A schematic drawing of the pheromone searching behavior of the silkworm.

by continuous feedback. Thus, the experimental results strongly support a hypothesis that the motion sequence of a silkworm moth to achieve pheromone source is a fixed instinctive behavior.

In the contrast, when we set unbalanced gain (1:4), the success ratio significantly decreases. We consider that a real-time feedback works hard to arrange behaviors. By our previous researches, we think that a silkworm moth arranges unbalanced motion based on visual information. Thus, the results support a hypothesis that visual inputs modulate behaviors quickly as reflex actions.

## 2.3 Adaptability of behavior to find a pheromone source

This research revealed that a silkworm synthesizes optomotor response and program behavior in order to achieve a pheromone source under uncertain dynamical situations (Fig. 4). However, we still have not had concrete map to show how optical input arranges motion commands. In our next plan, we observe optic flow by putting image sensors on the top of the robot. Then, we artificially arrange behaviors of the insect-controlled robot by using a model of optomotor response. If the robot behaves as Fig. 2, we can estimate that the arrangement is done in the lower part of a control system. Like this way, we can continue to reveal mechanisms of multi-sensor fusion. We will also investigate plasticity of neural systems by using insect-machine hybrid systems.

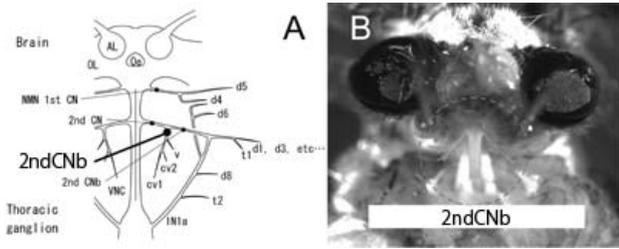


Fig. 5: Silkworm moth's nerves and 2ndCNb.

### 3 Cyborg: novel tool for analysis of dynamical brain systems

In this section, we describe a novel tool for analysis of dynamical brain systems. It is so-called "cyborg" that has living brain of an insect, computer to translate neural signals into motion commands, and driving motors on a robotic body<sup>5)</sup>. We have realized decoding motion commands in neural fibers and observed sequences of odor-source searching.

#### 3.1 Decoding neural signals

We observe motion commands from a brain through 2ndCNb of neck motor neurons. Left and right 2ndCNbs consist of five neural fibers each, and are connected to left and right neck muscles, respectively(Fig. 5:A). We cut fibers sending return signals from body to the brain, because we regard that the external inputs are more important than the feedback signals.

To translate neural activities into motion commands, we refer to behavioral researches<sup>6)</sup> that measures responses to one-shot stimuli of pheromone. We regards motions of a silkworm moth as follows; averaged rotational speed is about  $\pi/9$ [rad/s], maximum  $\pi/3$ [rad/s], averaged running speed is about 25[mm/s], maximum 80[mm/s].

We express motions of the body angle as  $\dot{\theta} = a\phi + C$ , where  $\theta$  denotes the body axis,  $\phi$  shows the angle of the neck, and  $a$  and  $C$  are static coefficients.

Let us formulate a translation from neural signals to motion commands. Let  $\phi_{max}$  be the maximum angle of the neck,  $n_l$  and  $n_r$  are counted pulse signals during 0.1[s]. Based on the preliminary experiments, we formulate simple dynamics of  $\phi$  as (1), where  $h$  is a fixed threshold, and  $n_d \triangleq n_l - n_r$ .

$$\phi = \begin{cases} \text{sig}(n_d) * \phi_{max} & (\text{if } |n_d| > h) \\ n_d * \phi_{max} & (\text{otherwise}) \end{cases}. \quad (1)$$

#### 3.2 Experimental system of insect-brain-driven robot

We have built a hardware of a cyborg, insect-brain-driven robot. This is a complete autonomous robot contains a brain, electrodes, amplifiers, microcontroller, motors and Bluetooth communication system (Fig. 6).

We have carried out pheromone-source-tracking experiments in a wind tunnel that is 840[mm] width,

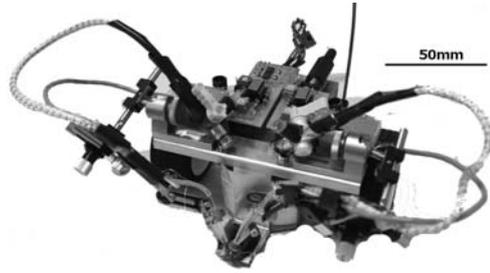


Fig. 6: Overview of the brain-machine hybrid system

1500[mm] length and 240[mm] height. Figure 7 illustrate a typical trajectory of the cyborg, where we put fan on the rightside of the figure, and the initial position of the cyborg was leftside. We have had 11

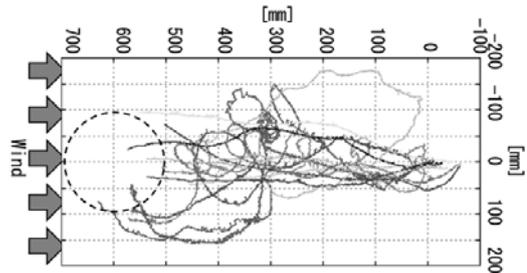


Fig. 7: Experimental trajectories.

achvements among 14 trials. We consider that our novel experimental system, cyborg, successfully expose adaptive behaviors although its size and mechanism are quite different.

### 4 Functional structure to exhibit program behavior

We have proceeded researches on functional mechanisms through nonlinear oscillator networks<sup>7)8)</sup>. Like the zigzag motion triggered by pheromone, a creature can exhibit considerably slower transitions than those of the elements in its brain. To understand a functional structure to generate such effect, we formulate a simple model and construct a network to exhibit long-lasting excitation (LLE) triggered by external inputs<sup>9)</sup>, and recalled the programmed behavior by introducing capacitive coupling.

Neural circuits often are modeled by oscillator networks because neurons fire in a vibrating manner. We employ phase oscillators as the simplest element in a network. Let  $\phi_i$  be a state of oscillator  $i$  and  $f(\phi_i)$  be its output function. We define  $f(\phi_j) = \cos^{20}(\frac{\phi_j}{2})$  to make impulse-like signal.

Let  $F$  (2) be a summarized output of a network, where  $N$  is the number of elements.

$$F(\phi) = \frac{1}{N} \sum_{i=1}^N f(\phi_i), \quad \phi = [\phi_1, \phi_2, \dots, \phi_N]^T \quad (2)$$

We design a dynamics of an element as (3), where

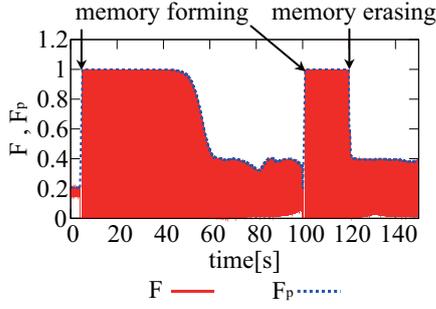


Fig. 8: Switching of  $F$  and  $F_p$  by external inputs

$a_{ij}$  becomes 1 when  $i$  and  $j$  are connected.

$$\dot{\phi}_i = \omega + \frac{\kappa}{N_i} \sum_{j=1}^N a_{ij} f(\phi_j) g(\phi_i) + \alpha_i + \beta_i \quad (3)$$

In the model,  $g(\phi_i) = \sin(\phi_i)$  represents sensitiveness, and  $\alpha_i$  and  $\beta_i$  show ignition and breaking switch, respectively.

Here, let us suppose the following approximations.

$$\begin{aligned} \dot{\phi}_i &\approx \omega + \frac{\kappa}{2\pi N_i} \sum_{j=1}^N a_{ij} \sin(\phi_i - \phi_j) \\ &\approx \omega + \frac{\kappa}{2\pi N_i} \sum_{j=1}^N a_{ij} (\phi_i - \phi_j) \end{aligned} \quad (4)$$

Then, we can express the dynamics of the system by using graph Laplacian  $L$  as (5), where  $\mathbf{1}_N = [1, 1, \dots, 1]^T$ .

$$\dot{\phi} = \omega \mathbf{1}_N + \frac{\kappa}{2\pi} L \phi \quad (5)$$

Because we can regard the phase gap as  $\psi_i$  in (6),

$$\psi_i = \phi_i - \frac{1}{N} \mathbf{1}_N^T \phi \quad (6)$$

Then, the dynamics can be formulated as (7), where the behavior is independent from original frequency  $\omega$ . The response just depends on  $L$ .

$$\dot{\psi} = \frac{\kappa}{2\pi} \hat{L} \psi, \quad \hat{L} \equiv (I - \frac{1}{N} \mathbf{1}_N \mathbf{1}_N^T) L \quad (7)$$

Based on the above formulations, we can build control systems to triggered by  $\alpha_i$  and stopped by  $\beta_i$ , and make analysis of duration of the response. Figure 8 illustrates an example to start and stop active oscillations by the external triggers.

We have extend this LLE system to recall the programmed behavior sequence of a silkworm by introducing capacitive couplers. Figure 9 illustrate motion commands to rightlegs (upper) and leftlegs (lower) after presentation of system input (pheromone) at 0. We can see that the system exhibits zigzag-loop behaviors by using oscillator network.

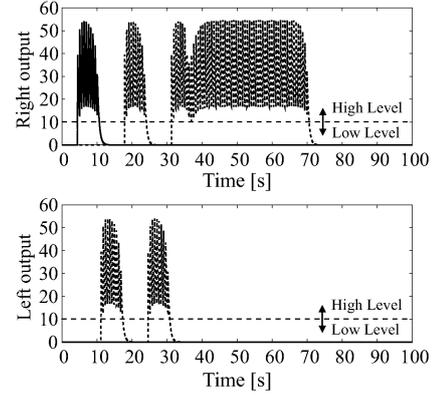


Fig. 9: Sequential pattern generated by the oscillator network

## 5 Conclusions

We have already built the novel experimental systems called bio-machine hybrid system, and have gotten some results. Our future plan includes analysis of functional structure in a micro brain by using multi-aspect experiments and constructive approach of mathematical formulations.

## References

- 1) R. Kanzaki, et al.: Self-generated zigzag turning of *Bombyx mori* males during pheromone-mediated upwind walking, *Zool. Sci.*, **9**, 515/527, 1992.
- 2) T. Mishima and R. Kanzaki: Coordination of flipflopping neural signals and head turning during pheromone-mediated walking in a male silkworm moth *Bombyx mori*, *J. Comp. Physiol. A*, **183**, 273/282, 1998.
- 3) S. Wada and R. Kanzaki: Neural control mechanisms of the pheromone-triggered programmed behavior in male silkmths revealed by double-labeling of descending interneurons and the motor neuron, *J. Neurol.*, **484**, 168/182, 2005.
- 4) S. Emoto, et al.: Insect- Controlled Robot - Evaluation of Adaptation Ability - *J. Robotics and Mechatronics*, **19**, 436/443, 2007.
- 5) A Takashima, et al.: Brain-Machine Hybrid System ?To Investigate Adaptability of an Insect Brain-, *Mobilibence2009*, 338/342, 2009.
- 6) R. Kanzaki and T. Mishima: Pheromone-Triggered 'Flipflopping' Neural Signals Correlate with Activities of Neck Motor Neurons of a Male Moth, *Bombyx mori*, *Zool. Sci.*, **13**, 79/87, 1996.
- 7) T. Funato, et al.: Switching Mechanism of Sensor-Motor Coordination through Oscillator Network Model, *IEEE Trans. SMC-B*, **38**(3), 764/770, 2008.
- 8) T. Funato and D. Kurabayashi: Network Structure for Control of Coupled Multiple Non-Linear Oscillators, *IEEE Trans. SMC-B*, **38**(3), 675/681, 2008.
- 9) T. Moriyama and D. Kurabayashi, An Oscillator Network with a Temporary Memory Function, *IEEE RO-BIO2008*, 2024/2029, 2009.

# Mobiligence Studies on the Physiological Systems that Control Social Behavior in Animals

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**Abstract**—In colonies of social insects like termites, there are various castes, among which tasks are allocated. As the results, we can see the elaborate social behavior in those insects. Social interactions also play important roles in the schooling behavior that is seen in fishes like medakas. Through various approaches, we are investigating the molecular and neurophysiological basis of organized behavior in animals, to understand the mechanisms and evolution of sociality, and to find out new concepts in relation to the autonomous decentralized systems.

## INTRODUCTION

There are diverse systems, which are recognized as self-organization systems or complex systems. Also in animals, lots of examples of interactions among individuals constructing social systems have been reported, although the underlying mechanisms that control such social behavior are largely unknown. In our project, two subthemes are now ongoing; one is on the social behavior in termites and the other is on the schooling behavior in fishes. Here, we report our recent progresses on the mobiligence studies on the projects.

### SUBTHEME I. REGULATIONS OF SOCIAL BEHAVIOR AND CASTE DIFFERENTIATION IN THE DAMP-WOOD TERMITE

Social Insects organize colonies, live together with their related individuals, and perform elaborate social behavior [1]. In the colonies, there are reproductive and sterile individuals, and those sterile ones are helpers that are engaged in altruistic tasks such as foraging, defense, etc. Those types of individuals that specialize in certain tasks are called 'castes'. Although there are diverse research subjects in the studies of social insects, one of the fundamental questions is that what mechanisms underlie the caste differentiation, and what types of neural modifications are required in the caste-specific behavior. Here, we summarize the recent progresses in our studies on the mechanisms regulating social behavior in the damp-wood termite *Hodotermopsis sjostedti*.

The termite social behavior is organized elaborately by task allocation and cooperation. In order to accomplish the

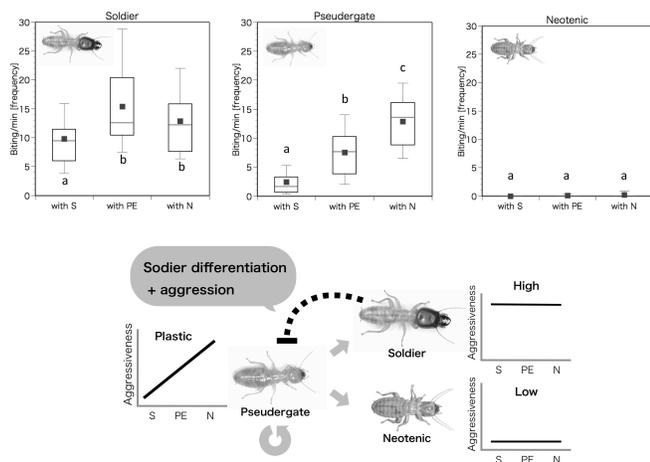
social behavior, there must be at least two intrinsic mechanisms in termites. The first mechanism is that all individuals possess a set of genes (a genome) that enable them to differentiate into any castes. Similar mechanism is seen in the cell differentiation of multicellular organisms, in which all of the cells include the genomic information that is required for any cells constituting the organismal body. The second mechanism is to regulate the caste ratio in a colony. If all of the individuals differentiate into soldiers, the colony should be destroyed because they lack reproductive options. For this reason, they have flexible options that can change the caste fate during their developmental processes. Namely, each individual can change the physiological status in response to the environmental factors, followed by the change of developmental pathways. Thus, by means of mechanism of "polyphenism" and "feedback", termites can realize the appropriate caste ratio under a certain environment [2].

### <Quantification of caste-specific defensive behavior >

Since termites can be target prey for various types of predators in nature, it should be important for termite fitness to appropriately defense against predators. So far, it has been thought that soldiers exclusively play defensive roles while workers also defense only indirectly by nest building behavior. On the other hand, some previous researches also have suggested the possibility that workers also show some aggressive behavior against predators. Actually, in some species, workers show some degree of aggression, especially against other colony members. Furthermore, in a nasute termite species, *Nasutitermes exitiosus*, it was also reported that workers showed extensive aggressive biting behavior against predatory ant species. However, no example has been reported, quantifying the differences defensive behavior between workers and soldiers.

In this study, therefore, we explored a new system to investigate the difference of defensive (aggressive) behavior among castes, using soldiers, workers, and neotenic reproductives in the Japanese damp-wood termite *Hodotermopsis sjostedti*. In the case when we put one isolated individual in a dish and a predatory ant was encountered, aggressive defensive behaviors like biting were more frequently seen in soldiers than workers, and less in neotenic. This tendency seemed to match the field observations.

In the next experiment, we examined the defensive behavior can be changed depending on the accompanied castes. As the results, the behavioral tendencies of soldiers and neotenic workers were constant regardless of accompanied castes, while the aggression of workers was changed (Fig. 1). In case workers were placed with neotenic workers, they tended to show aggressive behavior against enemies, while together with soldiers, they showed less aggression. This suggests that the presence of soldiers and neotenic workers respectively represses or promotes the aggression of workers. It has been known that the presence of soldiers inhibits the soldier differentiation from workers. However, as the differentiation requires more than one month, the prompt defense against emergency would be impossible solely by this mechanism. This flexible behavioral change seen in workers enables termite colonies to quickly defend against predators. Furthermore, as workers can differentiate into reproductives, when together with soldiers, they should survive to keep the reproductive potential in future (Fig. 1).



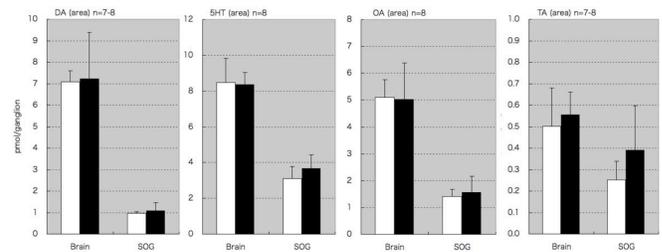
**Fig.1.** The caste differences in defense behavior in the damp-wood termite. While, soldiers show constant aggression regardless of accompanied castes (above left), workers show flexible aggression depending on the accompanied castes (above center). On the other hand, the aggression of neotenic reproductives is constantly low (above right). The flexible aggression in workers can be regulated by the existence of other castes (below).

<Differentiation of biogenic-amine systems in the soldier differentiation>

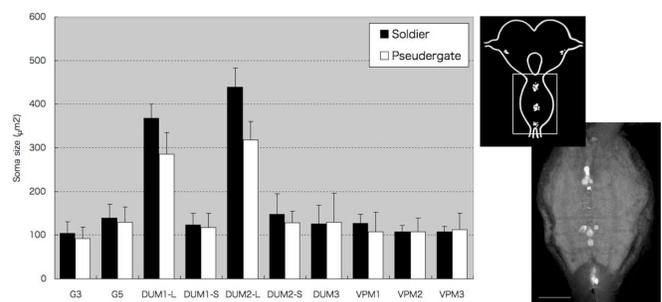
In the studies of social insects, there are lots of unraveled mechanisms underlying behavioral differentiation among castes. Our previous study showed that the nervous system of soldiers is specialized in the differentiation process [3]. This year, we analyzed how biogenic amine systems are involved in the behavioral specializations in soldiers. Firstly, concentrations of dopamine (DA), serotonin (5HT), octopamine (OA) and tyramine (TA) in brain and subesophageal ganglion (SOG) were quantified by HPLC. Unexpectedly, no differences of amine titers between soldiers and workers were detected (Fig. 2), although soldiers tended to have relatively higher titer of tyramine that is a precursor of octopamine.

It is generally known that neuroregulators including biogenic amines work locally at the site of secretion to regulate the sensitivity of adjacent synapses. Such locally regulated differences

between castes could not be detected in the measurements of whole brains. Therefore, in order to detect such local differences, we tried to visualize neurons producing amines by means of antibodies against them. In this observation, we first focused on octopamine, which is known to involve in aggression. The results of immunostains showed that there were 11 clusters of octopamine-producing neurons. The comparison between soldiers and workers revealed that two largest neurons (DUM1-L and DUM2-L) in the DUM1 and DUM2 clusters were more enlarged in soldiers than in workers (Fig. 3A). Other OA immunoreactive neurons showed no size differences. The intracellular staining of DUM1-L and DUM2-L neurons revealed that the projection sites of DUM1-L and DUM2-L neurons included tritocerebrum and mandibular muscles (Fig. 3B), suggesting that these neurons secrete octopamine to these target sites to promote the soldier-specific behavioral changes. In the future studies, further analyses on target sites of these neurons in addition to the functional analyses using antagonists and/or agonists will unravel the functions of biogenic amines in the behavioral caste differentiation in termites.



**Fig. 2.** Biogenic amine titers in the brain and the subesophageal ganglion (SOG) in soldiers and workers of the damp-wood termite. No significant differences were detected between the two castes.

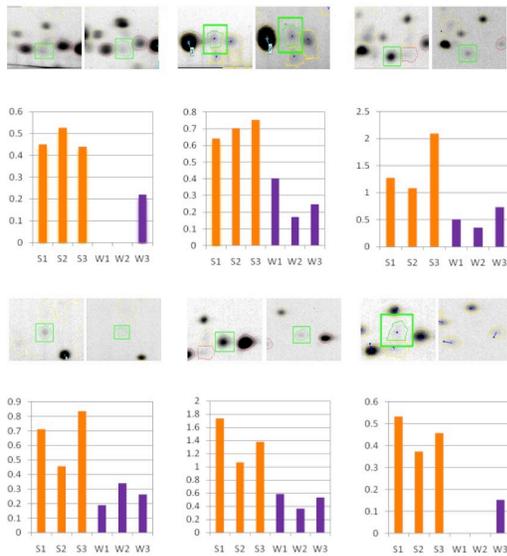


**Fig. 3.** Immunohistochemistry using anti-octopamine antibody revealed that the DUM neurons produce and secrete octopamine. In addition, some of the DUM neurons (1-L and 2-L) are enlarged specifically in soldiers.

<Caste-specific proteins identified in sternal glands>

Among various known exocrine glands in social insects, sternal glands in termites are well-known as secreting “trail pheromones.” Although the function of sternal glands is known for worker castes, it is not well understood for soldier caste. In this study, therefore, we analyzed the protein

components of sternal glands isolated respectively from workers and soldiers in *Hodotermopsis sjostedti*. For the first step, crude protein extracts were prepared from isolated sternal glands from soldiers and workers, and then they were examined by 2D-gel acrylamide gel electrophoresis. By comparing the obtained protein spots for workers and soldiers, as the results, six spots were identified as the soldier-specific sternal-gland proteins (Fig. 4). Interestingly, the molecular weights were less than 15kDa, showing that they are relatively small proteins. In addition, no worker-specific protein was identified. Based on the results, we are now able to discuss the sternal-gland function in soldiers. In the future studies, we will try to clone genes for the identified proteins in addition to the functional analyses of those proteins/genes, that will reveal the function of sternal glands in soldiers.



**Fig. 4.** The results of 2D-gel electrophoresis. The six identified spots for soldier-specific proteins are shown. In the analysis, technical triplicates confirmed the reproducibility. Most of the identified spots were soldier-specific, indicating that the soldier-specific function of sternal gland itself. The Y axes show the relative expression levels.

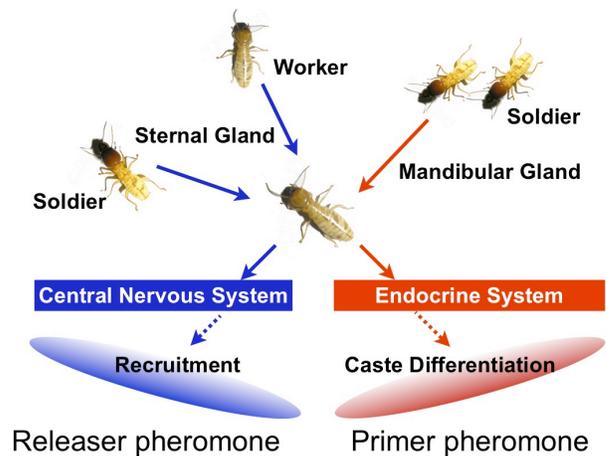
<Chemical analyses to identify pheromone molecules responsible for social communications >

Inter-individual communications are essential for the sociality in insects. In the case of termites, together with other eusocial insects, chemical communications using olfactory and gustatory systems are well developed. The chemicals used for communications among individuals in a single species are called “pheromones”, which can be categorized into “primer pheromones” that induce physiological changes of recipient individuals and “releaser

pheromones” that change recipient behaviors (Fig. 5). Our previous studies have found the caste-specific development and the caste-specific gene expressions in exocrine glands, suggesting that there must be some chemical communications by means of such caste-specific pheromones. Therefore, in this study, we explored caste-specific chemicals secreted from various exocrine glands and analyzed the functions by using bioassays.

As the results we assessed worker behaviors against the extracts from various exocrine secretions, secretions from sternal glands in workers and soldiers both showed the trail-pheromone functions. Furthermore, we tried to let termite workers choose the trail pheromones derived from worker- or soldier-sternal glands. Results showed that the pheromone from workers possessed more potential to induce the trailing behavior, suggesting that the sternal gland pheromones from workers or from soldiers possess different functions from one another, based on the qualitative or quantitative chemical properties.

We also tried to detect chemicals included in the exocrine glands by using gas chromatography, showing that some soldier-specific components were found from mandibular gland secretions. Although it is generally known that the chemicals derived from soldier heads repress the soldier differentiation from other individuals like workers, chemicals responsible for such caste regulations have never been identified. In the future studies, by the identification of chemicals followed by the determination of molecular structure and functional analyses, primer pheromones that regulate termite caste differentiation will be discovered.



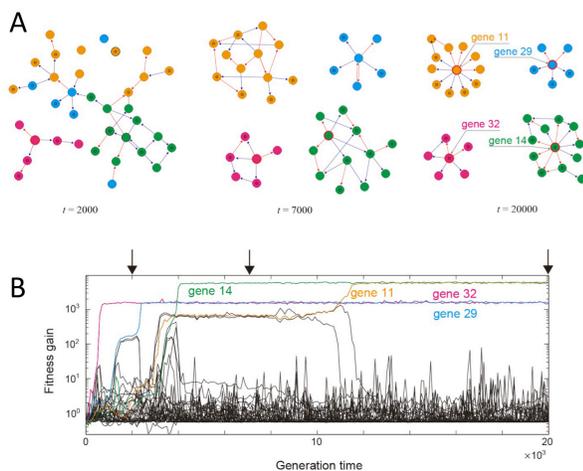
**Fig. 5.** Releaser pheromones were found to be secreted from sternal glands in the damp-wood termite (left). In addition, there are some soldier-specific chemical components found in mandibular gland, suggesting that the secretion may have caste-specific functions (right).

<Mathematical model for the evolution of modularity of gene expression networks promoted by developmental noises >

So far, we have been developed the mathematical models for caste differentiation in termite societies [4], in addition to the models for evolution of polyphenisms, by means of computer simulations. Those results indicate that developmental noises or fluctuations seem to be required for producing multiple phenotypes. This year, we tried to expand our model to more general phenomenon; we examined if the developmental noises can promote the modularization of gene expression networks by constructing new model and simulations with it.

It has been revealed that many gene networks have modular structures seen in various organisms, and studies exploring the evolutionary theory underlying the modularization have recently been accumulated. So far, a hypothesis was proposed, in which modular structures can evolve under the condition with repetitive directional selections in unstable environments because individuals with more modular structures individuals would be more adaptive because of less mutations against environmental changes.

We here propose another hypothesis; i.e. the evolution modular structures can be promoted by selection pressures on “phenotypic diversity derived from gene expression noises during developmental processes.” To assess the hypothesis, the evolutionary model for individuals with gene expression networks in which gene expression includes some noises under stable conditions was constructed and the mathematical simulations were carried out. As the results, it was shown that modularized structures were evolved in the gene expression networks by such developmental noises.



**Fig. 4. Results of mathematical simulation (A). Some modularized structures were evolved depending on the covariances for environmental niche distributions. Each gene network module possesses a “hub” structure. Resultant fitness gains for the mathematical simulation (B). In each module, there is a gene with high fitness gain.**

## SUBTHEME II. ANALYSIS OF MOLECULAR/NEURAL BASIS UNDERLYING SCHOOLING BEHAVIOR OF MEDAKA FISH

To clarify both molecular/neural basis and brain information processing underlying social interactions in vertebrates, we have focused on Medaka fish and established a novel behavior system to induce Medaka schooling behavior. Using this system, we are planning to identify internal factors (gene, neural network, brain regions) essential for Medaka schooling behavior. On the other hand, to estimate brain information processing underlying schooling behavior, we developed a mathematical modeling, which could explain actual fish movement.

First we analyzed coordinated movement of a pair of fish and demonstrated that adult medaka exhibited the cohesive movement but larvae did not, despite the fact that an optomotor response (OMR) could be elicited in larvae. It indicated that the brain function, required for mutual attraction, develops after hatch. Second, to analyze brain development after hatch in medaka fish, we mapped the zones of cell proliferation in the adult medaka brain and identified 17 proliferation zones (Kuroyanagi et al, Brain Res. in press). Finally, we analyzed a single medaka movement during OMR. When the visual stimulus oscillated in low temporal frequency (0.1Hz), the medaka responded with almost the same frequencies. In contrast, in high temporal frequency (1Hz), medaka did not. It implied that medaka may have an capacity like as " low-pass filter" to adapt environmental change by cutoff changes with high frequency (trivial changes).

## PERSPECTIVES

In this article, we introduced our studies on the mechanical basis underlying elaborate social life in termites and fishes. This year, the lots of experimental results were obtained on the physiological, neuronal and morphogenetic regulations in termites, in addition to the establishment of experimental systems on the schooling behavior in the medaka fishes. Based on these studies on social regulation in these animals, we will understand the elaborate systems of social organization in animals, and will obtain some clues to find out new concepts of autonomous decentralized systems that can be applied to the area of robotics.

## REFERENCES

- [1]Wilson EO (1971) *Insect Societies*. Harvard.
- [2] Miura T (2005) Developmental regulation of caste-specific characters in social-insect polyphenism. *Evol Dev* 7: 122-129.
- [3] Ishikawa Y, Koshikawa S, Miura T (2007) Differences in mechanosensory hairs among castes of the damp-wood termite *Hodotermopsis sjostedti* (Isoptera: Termopsidae). *Sociobiol* 50: 895-907.
- [4] Ikemoto Y, Ishikawa Y, Miura T, Asama H (2009) A mathematical model for caste differentiation in termite colonies (Isoptera) by hormonal and pheromonal regulations. *Sociobiol* 54: in press
- [5] Kuroyanagi Y, Okuyama T, Suehiro Y, Imada H, Shimada A, Naruse K, Takeda H, Kubo T, Takeuchi H (2010) Proliferation zones in the adult medaka (*Oryzias latipes*) brain. *Brain Res.*: in press.

# Colony-size dependent adaptive strategies in an ant society and their underlying self-organized regulation

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## I. RESOLUTION OF EVOLUTIONARY CONFLICTS IN HYMENOPTERAN SOCIETIES

Colonies of social insects are often regarded as superorganisms. Each colony, as a group of individual organisms, behaves like an adaptive unit, in which individuals are like cells and organs of this superorganism. However, evolutionary theories predict various conflicts in such a seemingly well-organized colony. The scientifically established conflicts are conflicts over sex allocation, male parentage, and reproductive allocation in hymenopteran (ant, social wasps and bees') societies. However, no theory has yet considered the evolution when a colony faces these three conflicts simultaneously. We tackled this issue by developing a dynamic game model, focusing especially on worker policing (Ohtsuki and Tsuji 2009). Whereas a Nash equilibrium predicts male parentage patterns that are basically the same as those of relatedness-based worker-policing theory (queen-multiple-mating impedes worker reproduction), we also show the potential for worker policing under queen-single-mating. Worker policing will depend on the colony size, or the stage of colony growth. Male production at an early stage greatly hinders the growth of the work force and undermines future inclusive fitness of colony members, leading to worker policing at the ergonomic stage. This new mechanism can explain much broader ranges of existing worker-policing behavior than predicted from relatedness. We have tested predictions of the above theory using the ant *Diacamma* sp. from Japan. The experimental results surprisingly well supported the prediction that worker policing will occur only in small colonies under monogyny and monandry.

The above results raised another question. How ants can sense the size of their own colony? In general, colonies of social insects shift their behavior in response to colony growth. How individual colony members can "sense" the changing size of the colony they belong is, however, largely unknown. In this paper we first reveal an explicit mechanism of colony size related behavioral regulation. In colonies of *Diacamma* sp. from Japan a mated worker (functional queen) effectively monopolizes reproduction by regularly patrolling in the nest. During the patrol she police selfish oviposition by other virgin workers. Appropriately, she spends on average a longer time in patrol when the colony is large (Kikuchi et al. 2008). We show a simple feedback mechanism regulates this activity shift, which seems to be an adaptive behavioral response to

changing colony size for the gamergate. We illustrate this feedback system using mathematical models and tested the models predictions qualitatively. Furthermore, we examined chemical ecological mechanisms underlying this social recognition.

## II. CHEMICAL COMMUNICATION OF INDIVIDUALS

Tandem running recruitment is employed by many ponerine ant species during nest relocations. In this recruitment system, each leader ant recruits only one nestmate at a time to a new nest site. In some species, it is reported that the tandem running is triggered by tactile signals on the cuticular surface of the leader's gaster, perceived by antennal touching by the following worker (follower). However, the chemical compounds are not yet identified in any species.

Such tandem running is also confirmed in the Japanese queenless ponerine ant *Diacamma* sp. from Japan. Our preliminary bioassays suggest the presence of chemical signals on the leader's abdominal cuticular surface to trigger the tandem running. This study aimed to identify the chemical compounds serving as a signal for tandem running in this species.

Immigration of the colony members to a new nest site was artificially induced by disturbing the old nest of *Diacamma* sp. from Japan. Following behavioral bioassay was conducted on each tandem pair. Gastasters were separated from fresh bodies of the workers and washed three times by *n*-hexane. After treated the test samples, each treated gaster was gently inserted between the leader and follower. Number of the followers attracted to the inserted gaster was counted, and tandem-following activity was evaluated.

Tandem-following activity was confirmed only in the extract of the Dufour's gland. Continuously polar/apolar separation, activity was confirmed only in the fraction eluted with *n*-hexane (apolar fr.). After AgNO<sub>3</sub>-silicagel column chromatography, the activity was observed in the fractions that contained unsaturated hydrocarbons.

There was only one component contained in the fraction, which gave a molecular ion at *m/z* 252 with diagnostic ions at *m/z* 55, 69, 83. Compared with the mass spectra and retention indexes after epoxidation, the compound is estimated to be (8)-heptadecene (C18:1).

We estimated the tandem-following pheromone of the ant *Diacamma* sp. from Japan as (8)-heptadecene (C17:1), and it was stored in the Dufour's gland which located in gaster part

of the ant. This is the first identification report of the tandem-following pheromone of the ants. We observed that the follower ants did not always touch the gaster of leader ants during the tandem running but keep following the leader ants while they sometimes walked apart. It can be interpreted by the volatility of (8)-heptadecene.

To identify the compound, we need to test the dose-response of the tandem-following activity among the natural compound from ant workers and synthesized isomers of 8-Heptadecene (*cis*-, and *trans*- 8-Heptadene), by which it can be confirmed which is the active compound.

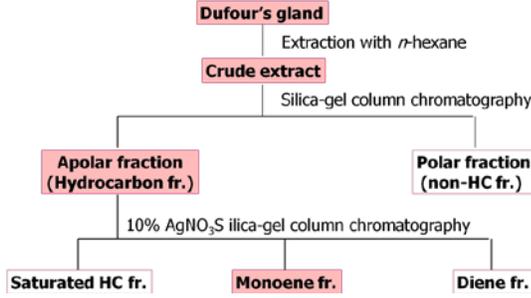


Fig.1 Fractionation of extract from Dufour's gland

### III. ANALYSIS AND MODELING OF ANTS' BEHAVIOR FROM SINGLE TO MULTI-BODY

We have engaged in constructing a model of ants' behavior from single level to multi-body level through the observations of *Diacamma sp.*

#### A. Fluctuations in single ant behavior

Fluctuations play a key role on micro to macro system, in biological system as well as physical system. We recorded a behavior of single ant in a field with no food, and measured the time evolution of its velocity and direction. From the spectrum analysis of walking velocity, we can see a long-term correlation in the velocity dispersion as shown in Fig.1 (left). We also found out the fluctuation is in proportion to the time scale ( $\sigma L \propto \Delta t^\alpha$ ), where  $\alpha > 0.5$  (Fig.1 (right)).

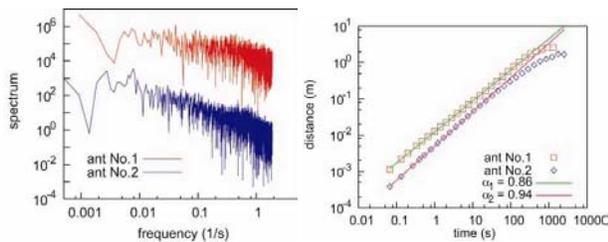


Fig.1. Power spectrum of walking velocity (left) and fluctuations of the velocity (right).

Based on the result, we describe single ant's behavior by simple mathematical model.

$$\begin{cases} L(t) = \bar{v} \cdot t + \int_{-\infty}^t ds \xi_L(s) (t-s)^{\alpha_L - \frac{1}{2}} \\ \theta(t) = \int_{-\infty}^t ds \xi_\theta(s) \end{cases} \quad (1)$$

#### B. Rhythmic component and entrainment of a few ant workers

In ant colonies, it is considered the essence of their collective behavior greatly depends on the local interaction of a few ants. In this research, we placed a few ants in hemisphere without a nest and food (Fig.2), and analyzed their location and velocity. (1) From the analysis of their trajectories, we found out that their trails show inhomogeneous distribution, and that the contact points of them distribute locally in the field (Fig.3). (2) From the analysis of velocity, we found out that their behavior includes rhythmic component in active-inactive state, and that anti-phase synchronization between two ants can be observed (Fig.4). We tried to explain this phenomenon by introducing a phase oscillator as an internal state and as phase oscillator and an entrainment of phase in two agents at each contact time.

$$\dot{\phi}_i = [\omega_i + \frac{K}{N} \sum_{j=1}^N \sin(\phi_j - \phi_i)] \delta(\vec{r}_j - \vec{r}_i) \quad (2)$$

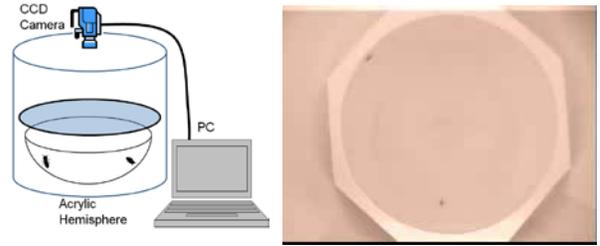


Fig. 2 Experimental setup

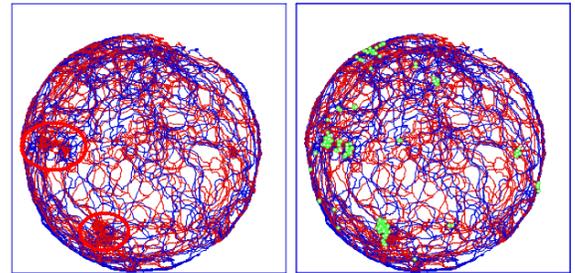
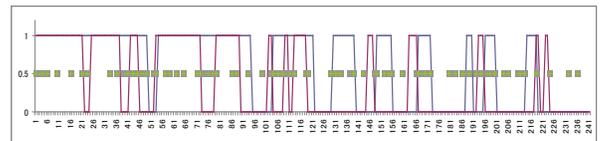


Fig.3. Trajectory of two ant workers (left) and contact points of them (right).



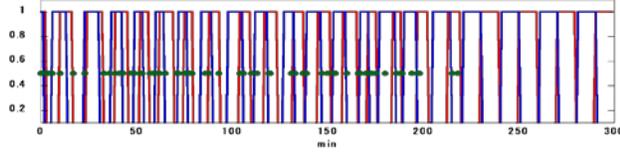


Fig.4. Binarized velocity of two ant workers and contact time(top). Simulation result (bottom).

### C. Modeling of patrol behavior

In the colony of *Diacamma sp.*, a gamergate walks around in the nest and comes in contact with the workers. The gamergate informs its presence to the workers by the physical contact. This behavior is called "patrol." It is reported the gamergate controls the patrolling time depending on the colony size. How does the gamergate know the colony size and control the patrolling time? What is the minimum model to describe this behavior? From experimental results, it is natural to introduce an internal state for each individual. We assume the gamergate has an internal state  $I_g$  which controls patrolling behavior, and each worker has an internal state  $I_{wi}$  which implies the condition of ovary. Based on the facts, we consider  $I_g$  is increased by the internal value of  $i$ -th worker, which the gamergate contacts.

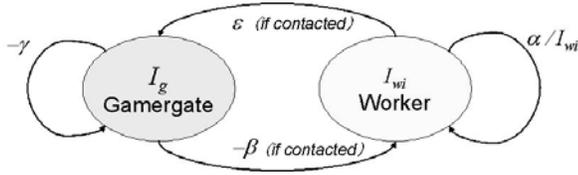


Fig. 5. Diagram of proposed model

As the egg production performance of each worker is inhibited by the physical contact, we assume the internal value of the worker decreases when it encounters the gamergate. Fig.5 shows the interaction of  $I_g$  and  $I_{wi}$ , and the dynamics of the system is described as follows:

$$\begin{aligned} \dot{I}_g &= -\gamma \cdot I_g + \varepsilon \cdot \delta(\bar{x}_g - \bar{x}_{wi}) \cdot I_{wi} \\ \dot{I}_{wi} &= \alpha / I_{wi} - \beta \cdot \delta(\bar{x}_{wi} - \bar{x}_g) \cdot I_{wi}, \end{aligned} \quad (3)$$

where  $x_g, x_{wi}$  denote the position of the gamergate and the worker  $i$ , respectively.  $\alpha, \beta, \varepsilon, \gamma$  are constant.  $\delta(r)$  denotes delta function. We also assume quiescence time  $\tau_q$  and walking time  $\tau_w$  of the gamergate depend on the probability as follows:

$$\begin{aligned} \tau_q &= \langle C_0 \cdot I_g \rangle \\ \tau_w &= \langle C_1 \rangle \end{aligned} \quad (2)$$

where  $C_0$  and  $C_1$  are constant. From computer simulation, we have confirmed that this model explain the behavior of gamergate qualitatively.

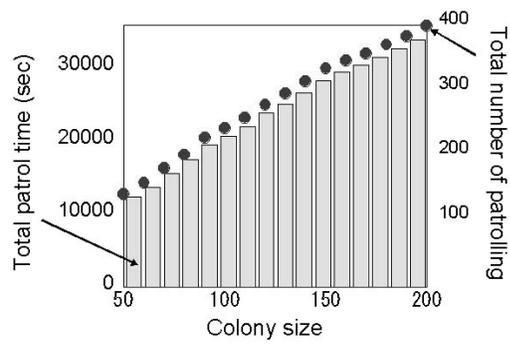


Fig.6. Total patrol time and total number of patrolling.

#### REFERENCES

- [1] Kikuchi, T., Nakagawa, T., Tsuji, K. 2008 Changes in relative importance of multiple social regulatory forces with colony size in the ant *Diacamma* sp. from Japan. *Animal Behaviour* **76** : 2069-2077.
- [2] Ohtsuki, H., Tsuji, K. 2009 Adaptive reproduction schedule as a cause of worker policing in social Hymenoptera: a dynamic game analysis. *The American Naturalist* **173**: 747-758.

# Synthetic Neuroethological Approaches for Understanding the Mechanism of Song Discrimination in Female Zebra Finches

Kotaro Oka, Fumihiro Takayama, Mai Iwasaki, Machiko Yamamoto, Masafumi Hagiwara, Ei-Ichi Izawa

**Abstract**—For last 4 years, we have tried to understand the function of Hippocampal formation (HF) with several imaging techniques: multi-color imaging of brain slices, multi-color neuron visualization with a gene gun and lipophilic fluorescent dyes, neuronal activity imaging with in situ hybridization of immediate early genes and also pH imaging. We succeeded to demonstrate that HF is one of the important regions for discrimination of bird songs in female zebra finches. In this report, we will show our achievement and the future plans for further understanding of HP function with synthetic neuroethological approaches.

## I. INTRODUCTION

ZEBRA finches communicate with their songs. Male finches have several kinds of their own songs and female finches choose the male for mating by his song. For understanding the song communication, information processing in the female brains is crucial. However, the neural network for the information processing in female brains has been poorly understood. For last 4 years, we have tried to understand the function of Hippocampal formation (HF) with several imaging techniques: multi-color imaging of brain slices, multi-color neuron visualization with a gene gun and lipophilic fluorescent dyes, neuronal activity imaging with in situ hybridization of immediate early genes and also pH imaging. We succeeded to demonstrate that HF is one of the important regions for discrimination of bird songs in female zebra finches.

In this report, we show our findings for neuroanatomy and neuronal activity of HF. Some of these imaging techniques are suitable for the large-scale and comprehensive study, comparing with conventional neurophysiological techniques.

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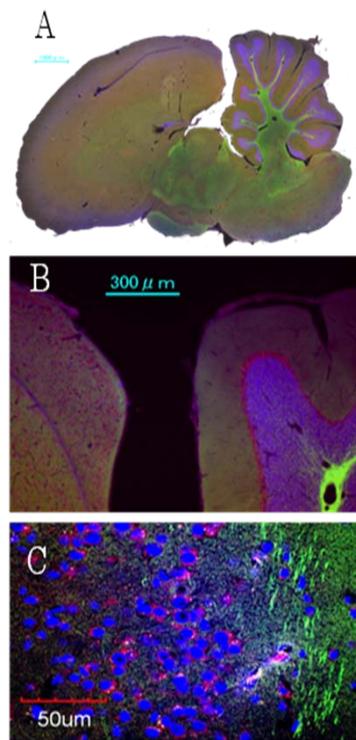
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## II. BASIC ANATOMICAL INFORMATION FOR HF

### A. Neuro-anatomy of female zebra finch brain

To understand the neural basis of the song discrimination in female zebra finches, one of the solid strategies is to investigate the neural architecture in HF and neural connection around HF regions. We adopted the usual neuro-anatomical approach with the multi-color staining with DAPI for nucleus, Nissl for neurons, and also fluoromyelin for neural axons covered with myelin. Using this method, we visualized the neural architecture in the whole male and female brains. To investigate the cytoarchitecture in HF in detail, we adopted the shot-gun like technique. The gene gun is usually used for the gene transfer to cells, but we used this technique to deliver the different types of lipophilic fluorescent dyes to the neurons by chance. We succeed to visualize each neuron with this method, and this technique enables us to exhaustive investigation of cytoarchitecture in HF (Fig. 1).

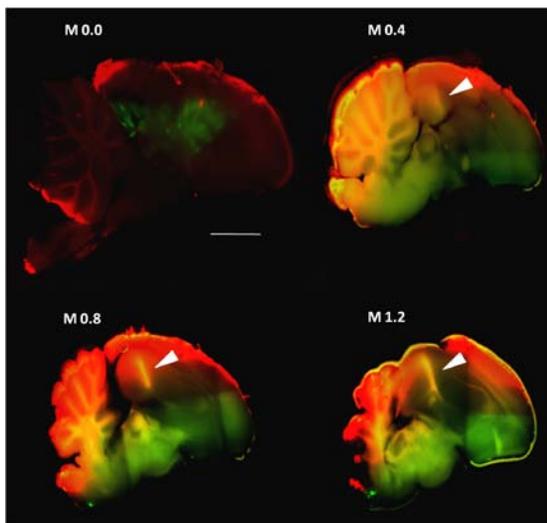


**Fig. 1** Fluorescent images of the brain in female zebra finch with low (A), middle (B) and high (C) power magnification.

We show that the low magnitude image of the sagittal section of female zebra finch brain (Fig.1A). Three staining was simultaneously presented: nuclei (dark blue; DAPI), myelinated-neuronal fibers (green; FluoroMyelin), and cell bodies of neurons (magenta; Nissl staining). In the deep regions in the brain, we can observe broad areas of myelinated-neuronal fibers, and clear regional differences are observed in the cerebellum cortex. A little higher magnification image reveals cytoarchitecture in HF (Fig. 1B). In HF, there is a V-shaped region with low density of DAPI staining. This kind of staining region was reported in the pigeon HF, and it is believed that corresponding region to dentate gyrus in mammalian HF. Furthermore, we investigated the cytoarchitecture of HF in detail (Fig. 1C). At the surface of the HF, there are myelinated-fibers. The direction of this fiber is from anterior to posterior. This structure is almost the same to the parallel fibers on the cerebral surface. In the following section, we report the spontaneous propagation of active areas in HF, and this propagation may concern to the direction of these myelinated-fibers.

### B. Neuronal connection between auditory cortex and HF

Sensory information is integrated at the HF, however, the contribution of HF to song perception or the direct connection between the auditory areas and HF has not been reported yet, although previous studies revealed HF's response to conspecific songs.



**Fig. 2 Multi-staining of HF and nuclei in auditory pathway.** DiI (shown in Red) stained HF neurons and projections from HF. DiO (shown in green) stained neurons in auditory pathway. The “M ” and a number represent the distance from the midline in millimeter. The arrowheads point to L2. Bar indicates 1 mm.

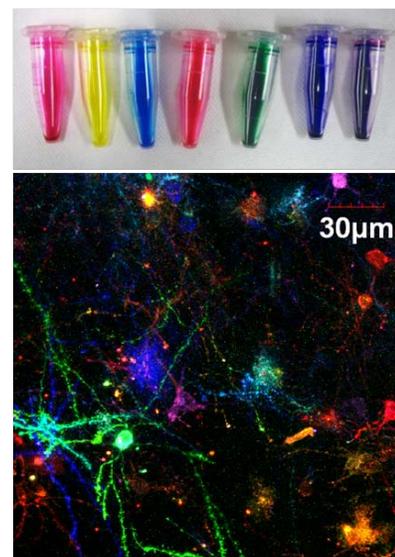
After dye-injection to HF (DiI) and auditory areas (DiO), the preparation was incubated for 4 weeks in 4 C to diffuse the dyes, for visualizing whole pathways of the neural projection. By this method, we can visualize the overlapping areas from HF and also from auditory areas. After dye diffusion, the

preparation was sliced sagittally with 400  $\mu$ m thickness. Among slices, the slice 1.6 mm external to mid-line showed a specific strong fluorescence from the two dyes at auditory area, L2 (Fig. 2, pointed in arrows), compared to its control. Fluorescence in L2 was also observed in other slices as well [1].

The dye-labeled L2 indicates that the HF has neural projection to L2. L2 has been known to discriminate conspecific songs from sound stimuli. Also, selective response in HF was observed by conspecific song stimuli though measuring the amount of immediately early gene, ZENK and FOS expression in female zebra finch. Since L2 has a role of discriminating conspecific songs and other sound stimuli, the direct connection between HF matches with the previous studies. Thus, the result demonstrates the direct connection between the HF and the auditory areas.

### C. Cyto architecture of HF

To elucidate the neuronal connection in HF, Golgi staining is one choice. Golgi staining visualizes the morphology of single neurons in detail, however, the staining is by chance and it is hard to determine the neuronal connectivity by this method because of its “black and white” staining image. We, therefore, applied a new staining technique with the gene gun and several types of lipophilic fluorescent dyes. This method enables us to stain the number of neurons in different fluorescent colors by chance, and also check the neuronal connectivity between stained neurons (Fig. 3B) [2]. We can observe the beautiful fluorescent color neurons in 30 min after dyes are applied to the slice preparation of brains. Fig. 3B is a stacked image from z-sections by a confocal laser scanning microscope, and the thickness of the stacked section is about 90  $\mu$ m. There are several numbers of different shapes of neurons; some of them have long dendrites with a lot of spines, and some of them have short dendrites.



**Fig. 3 Lipophilic fluorescent dyes (upper panel) and confocal image of HF (lower panel).**

From coronal and sagittal slice preparations, we have observed several types of neurons in crescent field (CF), lateral hippocampal complex (HCl), parahippocampal area (APH) and central field of the parahippocampus (PHc). Our results matched with the previous study done by Montagnese *et al* [3], but we have found smaller sized neurons and broader types of neurons not mentioned before (Table 1).

Table 1 Several types of neurons in HP subregions

Types of neurons	Soma size
Multipolar neuron	10 – 20 $\mu\text{m}$
Basket neuron	12 – 15 $\mu\text{m}$
Stellate neuron	5 – 10 $\mu\text{m}$
Pyramidal neuron	9 – 25 $\mu\text{m}$
Bipolar neuron	10 – 15 $\mu\text{m}$
Net-like neuron	10 – 15 $\mu\text{m}$

### III. NEURAL ACTIVITY IN HF

After investigating the neuronal architecture and neuronal networks in HP in detail, we started the work for detecting the neuronal activities of HF during hearing the songs. Usually, this kind of study is done as electrophysiological techniques. However, we tried to visualize the neuronal activity with fluorescent imaging technique because we had no spatial information of responding areas in HP. We used two methods: neuronal activity imaging with catFISH and pH indicator.

#### A. Neuronal activity imaging with catFISH

We used *Arc* (activity-regulated cytoskeletal-associated protein, one of immediate early genes or IEGs) catFISH (cellular compartment analysis of temporal activity by fluorescence in situ hybridization). This technique can visualize neural ensembles responded to two stimulations. Worley's group developed this technique for the study of rat hippocampus [4]. The key point of this technique is time-dependent subcellular localization of *Arc* mRNA. On induction, *Arc* mRNA can be detected first only in the nucleus and later only in the cytoplasm. This property is characteristic for *Arc* mRNA, not like other IEGs used for neural activity marker such as *c-fos* and *zenk* mRNA. Using this property, catFISH is performed by providing two stimulations. Second stimulation provided after appropriate time interval from first stimulation, neurons which respond the first stimulation have *Arc* mRNA in the cytoplasm, which respond the second stimulation have *Arc* mRNA in the nucleus. Thus we can discriminate which neurons respond the first or/and second stimulation. In this study, we used two songs (song A and B) as auditory stimulations [5].

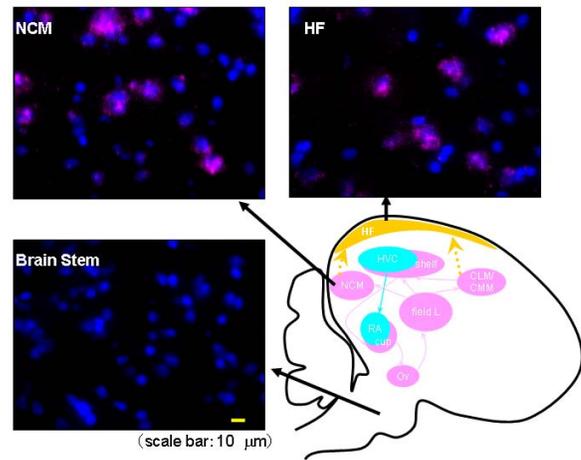


Fig. 4 Regions of *Arc* mRNA expression by song.

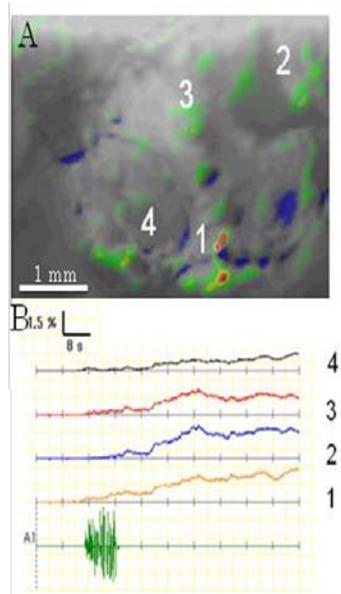
We investigated the expression pattern of *Arc* mRNA in female brains, especially hyperpallium, brain stem, cerebellum, HF and caudal medial nidopallium (NCM). The signals from these regions are quite different (Fig. 4). In brain stem and cerebellum, no signals were observed. The brain stem and cerebellum contribute to the generation of motor patterns of songs, but no relation has been reported for hearing and recognition of bird songs. No responses in these regions are, therefore, reasonable. One of the interesting findings is the responses observed in HF. Although no relationship to the auditory systems and HF has been reported in bird brains, hippocampus can be used for the spatial recognition and memory in several bird species, especially that hide the food during winter season.

Two kinds of male song are presented to the female finches with 50 min interval. After the song presentation, the numbers of cell with *Arc* mRNA signals were counted in CMM and HF. Sequential presentation of Song A and Song B induces different populations of neurons in CMM and HF. In signal-detected neurons, about 60% of cells responded to Song A and also Song B. Only 20% of neurons responded to either song. This ratio is almost same in HF. The birds with the same song presented twice showed relative high ratio (73%) of cells with nuclei and cytoplasmic signals. We have to investigate further the meaning of the information coding in CMM and also HF.

#### B. Neuronal activity imaging with pH indicator

We observed the response patterns in the HF when the female zebra finch was exposed to various sound stimuli (male song and reversed male song) by *in vivo* pH imaging [6]. We used a fluorescent pH indicator, neutral red (NR), that is sensitive at physiological pH range with large fluorescent change. NR has been used to monitor neuronal activity. NR stains neurons by simply incubation and does not leak from living cells. Neuronal excitation increases NR fluorescence up to 10 times more than voltage sensitive dyes. The pH-independent NR responses are likely to be evoked by neuronal depolarization, although intracellular mechanisms

that link depolarization to fluorescence enhancement are still unclear.



**Fig. 5** Song-induced neural activity changes in female HF. A) Pseudo-color image of pH response in HF. B) Time-course of pH responses in several areas in A. The lower trace indicates the timing of stimulation.

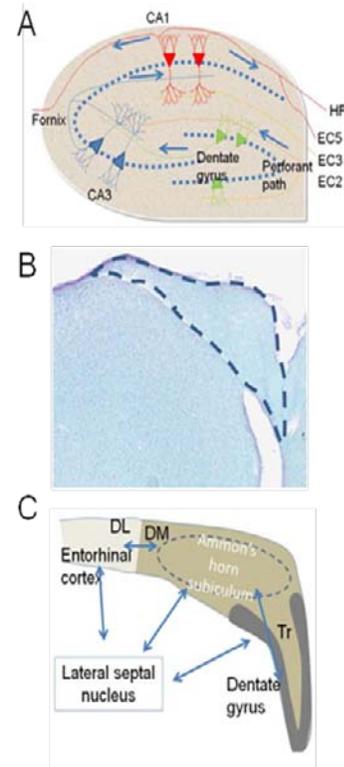
One of the interesting findings from pH imaging is the spontaneous neuronal activity and its propagation in HF. The amplitude of this response is 3 to 6 % of  $\Delta F/F$ , and it corresponds to acidification from pH7.4 to 7.3. We applied the several types of sound to female birds including white noise, call, pure song, reversed-song, combinatorial song. We reported that some of the songs induced neuronal activities in HF. We found two types of neuronal activities: one is no latency and another one with long latency. Neuronal activities with no latency frequently show the propagation of active regions in HF (Fig. 5).

#### IV. CONCLUSION AND FUTURE WORK

In last 4 years, we investigated the neuronal function of HP, especially concerning the song recognition and discrimination in female zebra finches. At just start this project, we found the so many things were unknown, and some of the information is lack to construct the mathematical models. We, therefore, started our research work from the construction of large-scale and comprehensive approaches to investigate the neuroethological information about the brain of female zebra finches. In this report, some of the new techniques we developed are presented. Using these new methods, we acquired the huge volume of the information for synthetic neuroethology for bird song recognition: 1) direct neuronal connections between the higher auditory cortex and HP, 2) findings of several new types of neurons, 3) visualization of neuronal activities induced by songs in HP.

Furthermore, we mention the direction of future plans of the experiment. In Fig. 6, I show the comparison of HP in

mammals (Fig. 6A) and zebra finch (Fig.6 B, C). Recently, the correspondence areas of HP subregions are described [7]. If we can prepare the slice preparation of HP in zebra finches, real time neuronal activities will be visualized with not only pH imaging, but also  $Ca^{2+}$  imaging. Time resolution of the  $Ca^{2+}$  imaging is higher than the pH imaging, and S/N ratio is high compared to the membrane potential imaging. We, therefore, can bridge the gap between the in vivo pH imaging with low spatial resolution and catFISH with high spatial resolution.



**Fig.6** Comparative anatomical study of mammalian (A) and zebra finch (B, C) HFs

#### REFERENCES

- [1] Yamamoto M, Takayama F, Fujimura A, Hotta K, Oka K. 2009. Proceedings of the 3<sup>rd</sup> international symposium on mobiligenesce 285-290
- [2] Gan WB, Grutzendler J, Wong WT, Wong RO, Lichtman JW. 2000. Multicolor "DiOlistic" labeling of the nervous system using lipophilic dye combinations. *Neuron*. 27(2):219-25.
- [3] Montagnese CM, Krebs JR, Meyer G. 1986. The dorsomedial and dorsolateral forebrain of zebra finch, *Taeniopygia guttata*. *Cell Tissue Res*. 283: 263-282.
- [4] Guzowski, JF, McNaughton BL, Barnes CA, and Worley PF. 1999. Environmental-specific expression of the immediate-early gene *Arc* in hippocampal neuronal ensembles, *Nature Neurosci*. 2: 1120-1124.
- [5] Fujimura A, Hotta K, Oka K. 2007. Proceedings of the 2<sup>nd</sup> international symposium on mobiligenesce 215-218.
- [6] Takayama F, Yamamoto M, Horita H, Hotta K, Oka K. 2009. Proceedings of the 3<sup>rd</sup> international symposium on mobiligenesce 291-294
- [7] Atoji Y, Wild MJ. 2007. Limbic systems in birds: morphological basis. Watanabe S, Hofman MA (eds.) *Integration of comparative neuroanatomy and cognitive*. 97-123, Keio Univ

# The Effect of Gaze as Central Cue on Horizontal Distribution of Attentional Field

Motoichiro Kato, Shuhei Nakamoto, Mihoko Otake, Hajime Asama

**Abstract — Eyes catch our attention. A paradigm to test the implicated role of eyes in orienting attention toward relevant target is the spatial cueing task using cues such as gaze and arrow direction. However, in the previous studies on this effect, the distance between the central cue and target was constant. In the present paper, by changing the distances, we examined the strength of attentional field elicited by central cues. We also compared the effects of seven cues (without cue, left/neutral/right arrow cues, and left/neutral/right gaze cues). The results showed two main findings; gaze cues enhance the attention more than arrow cues as a whole, and the appearance effect of the cues decreases as the increased distance from the fixation point, while the inducing effect by cues is independent of the distance.**

## 1 Introduction

Eyes are crucial for human interactions as social signals. They attract our attention because they provide us with information about feelings and intentions. For example, eye gaze tells us whether other person looks at us.

A experimental paradigm to test the implicated role of eyes in orienting attention toward relevant stimuli, is the spatial cueing task using cues such as gaze and arrow direction (Friesen and Kingstone, 1998; Tipples, 2002). In these tasks, where central gaze/arrow is used to trigger attentional orienting, normal subjects have repeatedly demonstrated faster reaction times in detecting peripheral targets presented congruently to the cue direction, opposed to incongruently presented targets.

It has been reported that patients with a lesion in the amygdala or the superior temporal sulcus (STS) showed different results from normal subjects (Akiyama et al, 2006a, 2006b, and 2007) In the gaze condition, patients with a lesion in the amygdala showed smaller congruency effects in the gaze condition, and patients with a lesion in

the STS had difficulty discriminating the direction of gazes. However, both patients made less difference from normal subjects in the arrow condition. Therefore, gaze information, that is biological signal, appears to be processed in the amygdala and the STS, while arrow information, that is non-biological signal, in different regions of the brain. Besides, people with schizophrenia, who are thought to have lesions in these regions, showed similar results (Akiyama et al, 2008). Therefore, researches on gaze recognition are important as clues to understand the pathology of these disorders and to elucidate the human interaction.

However, to date, there are few experiments on the changes of the visual attentional field elicited by arrow or gaze cues. For example, Handy (1996) showed enhanced attention within about 2.5 ° from the direction of the cue. Handy's study, however, didn't take into account the distance between the target and the cue.

We therefore expand the measurement range in order to investigate the strength of the attentional field elicited by gaze and arrow cues. Moreover, experiments are designed to separate the appearance or inducing effect from overall results.

## 2. Method for measuring the attentional Field elicited by gaze and arrow

Eight elderly adults and ten students participated in the experiment.

There were three conditions of seven cue types (without cue, left/neutral/right arrow, and left/neutral/right gaze). In the no-cue condition, we can examine the normal attentional field when the fixation point was at the center of the monitor. In the arrow or gaze condition, we can find out the effects of cue directionality. The difference between arrow and gaze cues is whether they are biological or not.

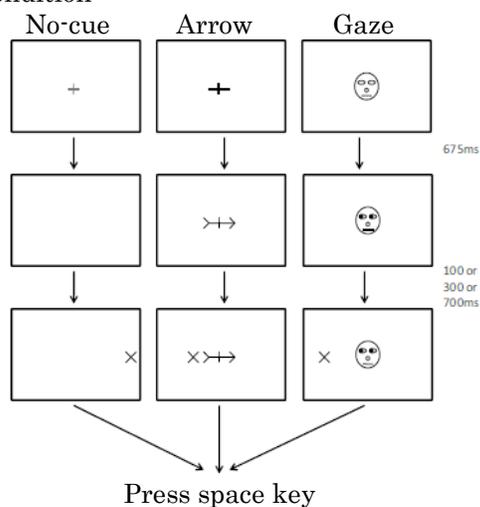
The factor affecting reaction times (RTs) is not only the inducing effect caused by directionality of arrows or gazes but also the appearance effect caused by the target onset.

Therefore in this experiment, cues were designed in order to separate these effects.

The RT difference between neutral condition and left and right condition represents inducing effects of the cues. The RT difference between the no-cue condition and neutral arrow condition represents the effect caused by the onset of figure (appearance effect of figure), while the difference between the neutral gaze condition and neutral arrow condition represents the effect caused by biological factors (appearance effect of face).

Trial sequence is illustrated in Figure 1. Trials began with the onset of a fixation figure. The fixation figure is a cross in the no-cue condition, a horizontally long cross in the arrow condition, and a face with blank eyes in the gaze condition. After 675 ms, the left/neutral/right cue was presented on the monitor. Then, after 100, 300 or 700 msec (stimulus onset asynchrony; SOA), the target appeared at the randomized point on the horizontal line. Subjects were instructed to press the space bar as quickly and accurately as possible when the target appeared. The range of target locations is  $\pm 16.1^\circ$  in the no-cue condition and  $-16.1^\circ \sim -2.0^\circ$  or  $2.0^\circ \sim 16.1^\circ$  in the arrow/gaze condition.

Figure 1 : Flow of experiment Condition

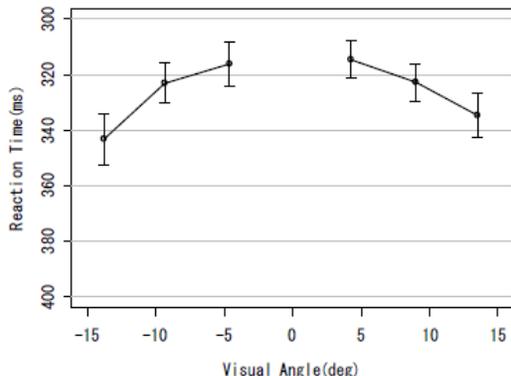


### 3. Results

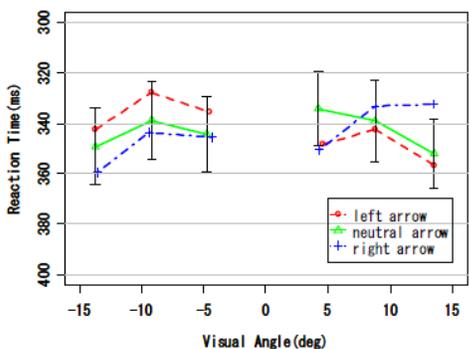
An ANOVA with cue type (without cue, arrow, and gaze) and cue direction (left, neutral, right) and t-test were conducted. Errors, defined as anticipations (RTs < 100 ms) or incorrect responses (RTs > 800ms) were excluded from further analysis. These errors accounted for 1.2% of all the trials. Then, trials at the 100 ms SOAs are also excluded because they had less inducing effect (details are given in "Difference between SOAs"). In analysis, we divided the range into six sections ( $-16.1^\circ \sim -11.6^\circ$ ,  $-11.6^\circ \sim -7.0^\circ$ ,  $-7.0^\circ \sim -2.0^\circ$ ,  $2.0^\circ \sim 7.0^\circ$ ,  $7.0^\circ \sim 11.6^\circ$ ,  $11.6^\circ \sim 16.1^\circ$ ), and RTs within each section were averaged. Note that the vertical axis was inverted so that we can see quickness as strength of attention.

The main effect of cue type was significant [ $F(2, 6711) = 41.24, p < 0.001$ ]. In the no-cue condition, RTs within the section near the fixation point ( $0^\circ$ ) were shorter than those near the edge (Figure 2). The average RT in the arrow condition was 19 ms longer than that in the no-cue condition [ $t(4447) = -8.46, p < 0.001$ ] (Figure 3). In the neutral arrow condition, there was no significant difference between visual fields [ $t(659) = 0.18, p = 0.86$ ]. In the left arrow cue condition, the average RT in the LVF was 14 ms shorter [ $t(784) = -2.69, p < 0.01$ ]. In the right arrow cue condition, the average RT in the RVF was 11ms shorter while one of the RTs was longer than that in the LVF [ $t(784) = 1.98, p = 0.048$ ]. The attention had a tendency to decrease as the distance from the fixation point increased. The comparison between cue directions showed no significant difference (left arrow:342 ms, neutral arrow:343 ms, right arrow:344 ms)[ $F(2, 2268) = 0.16, p = 0.86$ ]. The average RT in the gaze condition was 6 ms longer than that in the no-cue condition [ $t(4341) = -3.04, p < 0.01$ ] (Figure 4). In the right gaze condition, the average RT in the RVF was 8 ms shorter [ $t(797) = 1.82, p = 0.07$ ]. In the same way as in the arrow condition, the attention had a tendency to decrease, and the comparison between cue directions showed no significant difference [ $F(2, 2251) = 0.89, p = 0.41$ ].

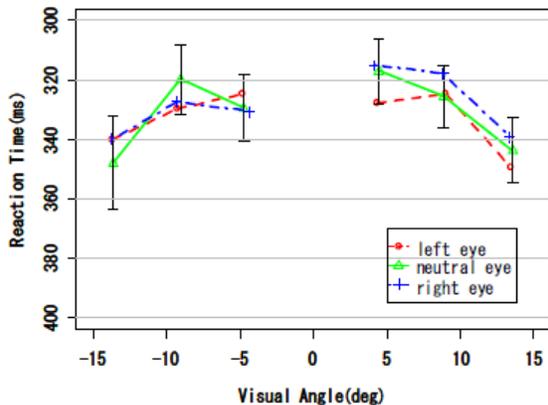
**Figure 2**  
Reaction time without cue  
(Error bars show 95% confidence range)



**Figure 3**  
Reaction time to arrow cues  
(Error bars show 95% confidence range)  
○: left arrow, △: neutral arrow, +: right arrow



**Figure 4**  
Reaction time to gaze cues  
(Error bars show 95% confidence range)  
○: left gaze, △: neutral gaze, +: right gaze



### 3.1 Appearance effect

The effect of the target onset (appearance effect of figure) obtained by subtracting the RT in the no-cue condition from that in the neutral arrow condition resulted in the 17 ms (delay). As the distance from the fixation point increased, the appearance effect of figure decreased in the LVF but not in the RVF. The effect of the face target (appearance effect of face) obtained by subtracting the RT in the neutral arrow condition from that in the neutral gaze condition resulted in the -12 ms in the LVF and -13 ms in the RVF (facilitation). The appearance effect of face decreased in both of the visual fields.

### 3.2. Inducing effect

We investigated the inducing effect of the cues by subtracting the RTs in the left or right cues from those in the neutral cues. The inducing effect of the left arrow cue resulted in -9 ms (facilitation) in the LVF and 8ms (delay) in the RVF (Figure 11). On the other hand, the inducing effect of the right arrow cue resulted in 6 ms in the LVF and the facilitation by -3 ms in the RVF. In contrast to the appearance effect, there was no remarkable decrease in the LVF and, there was some increase in the RVF. The inducing effect of the left gaze cue resulted in -1 ms in the LVF and 5 ms in the RVF. Likewise, the inducing effect of the right gaze cue resulted in 0 ms in the LVF and -5 ms in the RVF. As well as in the arrow cues, there was no remarkable decrease in both the visual fields.

### 4. Conclusion

The attention without cue was the highest near the fixation point and decreased as the distance from the center increased. In the left and right arrow and right gaze condition, there were significant cueing effects, which had been repeatedly observed since Friesen and Kingstone (1998).

In the arrow and gaze condition, the strength of attentional field decreased as well as in the no-cue condition. This result may be

affected strongly by the attentional feature of humans, which was evident in the no-cue condition.

The appearance effect of figure (the decrease of attention by the cue onset) is possibly a kind of gap effect. This term refers to faster responses to a peripheral target in the condition with offset of the fixation stimulus than with the condition where the fixation point remains visible (Dorris & Munoz, 1995) (Senju & Hasegawa, 2005).

The gaze cues which have biological features, facilitated RT by -12 ms (appearance effect of face). Probably, this resulted from stronger interest in the human face and boredom with the arrow cues. Although similar effects were apparent in some studies (Akiyama et al., 2006b), they didn't pay much attention to the effects of face because what has been discussed was the difference between congruent and incongruent condition.

The inducing effect calculated by subtracting the RTs in the neutral condition from those in left and right condition showed the benefit in the congruent condition. It is notable that the left gaze condition, which didn't have the benefit in "overall results", showed the inducing effect in the LVF. The inducing effect didn't decrease and sometimes increased at the edge of the monitor. This result indicates that an arrow and a gaze has the information about direction (e.g. likely to appear to the left), but not about distance (e.g. likely to appear at  $\circ$  cm from the center). This coincides with Calder and Young's model (Calder & Young, 2005), which separates between the recognition of facial identity and facial expression (gaze direction).

In summary, the present study expand the target area in the visual field, and revealed the strength of attentional field (distribution of attention) elicited by arrow or gaze cues. The results supported previous observations and revealed several new findings;

(1) In the arrow and gaze condition, attentional curve has its peak near the center and decrease monotonically

toward the edge.

- (2) Gaze cues facilitate attention more than arrow cues.
- (3) The appearance effect decreases toward the edge.
- (4) The inducing effect doesn't decrease toward the edge.

## References

- Akiyama, T., Kato, M. et al (2008). Gaze-triggered orienting is reduced in chronic schizophrenia.. *Psychiatry Research*, 158,287–296.
- Akiyama, T., Kato, M. et al (2006a). A deficit in discriminating gaze direction in a case with right superior temporal gyrus lesion. *Neuropsychologia*,44, 161–170.
- Akiyama, T., Kato, M. et al (2006b). Gaze but not arrows: A dissociative impairment after right superior temporal gyrus damage. *Neuropsychologia*,44,1804–1810.
- Akiyama, T., Kato, M. et al (2007). Unilateral Amygdala Lesions Hamper Attentional Orienting Triggered by Gaze Direction. *Cerebral Cortex*, 17, 2593–2600.
- Barbara, A et al (1994). Visual attention mechanisms show a center-surround organization. *Vision Research*,35, 1859–1869.
- Calder, A. et al (2005). Understanding the recognition of facial identity and facial expression. *Nature reviews Neuroscience*, 6, 641–651.
- Dorris, M.C. & Munoz, D.P. (1995). A neural correlate for the gap effect on saccadic reaction times in monkey. *Journal of neurophysiology*, 73, 2258–2562.
- Driver, J. et al (1999). Gaze Perception Triggers Reflexive Visuospatial Orienting. *Visual Cognition*, 6, 509–540.
- Friesen, C. K. & Kingstone, A. (1998). The eyes have it! Reflexive orienting is triggered by nonpredictive gaze. *Psychonomic bulletin & review*, 5, 490–495.
- Friesen, C. K. & Kingstone, A. (2003). Covert and overt orienting to gaze direction cues and the effects of fixation offset. *Neuroreport*, 14, 489–493.
- Handy, T. et al (1996). Spatial distribution of visual attention: Perceptual sensitivity and response latency. *Perception & Psychophysics*, 58, 613–627.
- Okada, T et al (2006). Right hemispheric dominance in gaze-triggered reflexive shift of attention in humans. *Brain and Cognition*, 62, 128–133.
- Posner, M.I. (1980). Orienting of attention. *Journal of Experimental Psychology*, 32, 3–25.
- Senju, A. & Hasegawa, T. (2005). Direct gaze captures visuospatial attention. *Visual Cognition*, 12, 127–144.
- Tipples, J. (2002). Eye gaze is not unique: Automatic orienting in response to uninformative arrows. *Psychonomic Bulletin & Review*,9, 314–318.

# Social Experience Contributes the Development of Instinctive Behavior in Male Crickets

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**Abstract**—Insects can exhibit complicated behavior, such as sexual behavior, aggressive behavior, etc. according to their environment using only tens of thousands of neurons. In the case of male crickets, growth environment have a great effect on the exhibition and development of instinctive behavior which have been thought innate. The mechanism controlling the development of behavior through social experience is considered to be included also in the cricket as a common principle which guarantees the adaptability of behavior. It seems likely that biogenic amines control not only the motivation of sexual and aggressive behavior, but also the development of such behaviors.

## I. INTRODUCTION

It is not difficult to make the robot which can respond to the predictable change of the environment, using the leading edge technology. However, realization of a robot becomes extremely more difficult as it becomes difficult to predict an environmental change. Therefore, from an engineering viewpoint, an insect will just be a mountain of the precious article of a design. Nevertheless, the insect attracted attention from innate stereotyped behavior rather in many cases, and comparative animal physiology and neuroethology have directed energy towards the elucidation of the neural basis of an innate releasing mechanism. Therefore, at an extreme case, development was sometimes seen as a subject for embryologists, of little relevance to behavior.

On the other hand, genetic approach to the development of behavior brought a lot of results about the role of genes in the development of the nervous system, and hence behavior. Behavior geneticists represented by S. Benzer have kept insisting the basic belief that the structure and function of the nervous system, and hence the behavior of an animal, is specified by the genes which are held to “contain the information for the circuit diagram”. What is the extent of the role of genes in the development of the behavior of an individual?

Genes quite clearly do not contain a circuit diagram for the nervous system. Circuit diagrams are isometric with the structures they represent. The nervous systems and behavioral repertoires of animals cannot be broken into units or group of genes. Nor does each gene affect only one character.

If genes are not a scale model, then in what sense could they direct development? Genes may embody a program for the construction of the nervous system. This must mean that,

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in some sense, a sequence of instructions, isometric with the sequence of developmental events, is present in the genes. Certainly, to suggest that genes alone can build nerve cells is misleading; nerve cells and all other cell types arise only by division of pre-existing cells.

Behavioral adaptations are so exquisite that they demand an answer to the question of what processes might have generated the beautiful fit between the animal and its environment. An adequate solution is not necessarily provided by merely asking whether or not learning was involved in the development of the individual animal. Behavior that has evolved in response to natural selection during evolution may, nonetheless, involve learning during its development.

It is difficult to design the adaptive behavior corresponding to environmental change in engineering, because how fixed action pattern and learning should be involved depends upon the degree of environmental change. It is surprised that simple animals like insects also have complicated adaptive behavior as the vertebrate with complicated structure being natural. Although it is surprise that the exquisite adaptive system is constituted by only tens of thousands of neurons itself, it is further surprised by that the mechanism into which such a system is developed in the process of ontogeny is involved.

Natural selection acts on the outcome rather than directly on the mechanisms by which that outcome is reached. Learning by experience may be an adaptive way of gearing the behavior of an animal to its own particular environment, but it is not necessarily the best way. It may not be open to animals with short lives or simple nervous systems. Where the first encounter with a predator may be a lethal one, it is also essential that the young animal behaves appropriately without experience of that situation. One of the interesting things about development is the discovery of just where specific aspects of experience have an influence and where they do not.

## II. INSTINCT BEHAVIOR AND ITS MOTIVATIONAL CONTROL IN MALE CRICKET

It is often assumed that behavior patterns which vary a lot from one individual to another are those which are less dependent on genetic influences and more on influences from the environment. Similarly, the behavior patterns most constant throughout a species are sometimes suggested as being those least influenced by the environment: such as fixed action patterns<sup>1)</sup>.

The male cricket *Gryllus bimaculatus* stridulates the courtship song before copulation. Once a male has consummated a copulation, the animal ceases courtship behavior for a while. In the absence of courtship behavior, other forms of behavior such as feeding, drinking and fighting are displayed. It appears as if copulation raises the threshold of courtship and in consequence a subordinate repertoire takes over. Between spermatophore protrusion (SP) and courtship stridulation (CS), there is a fixed time interval. This interval lasts about 1 h. During the period from SP to CS, the male cricket does not stridulate nor make any type of mating sound (post spermatophore protrusion silence: PSPS) and tolerates external sensory stimuli.

We examined the effects of injections of hemolymph and CNS extracts on the interval. Extracts obtained from crickets which had just started CS (CS crickets) and those which had finished SP (SP crickets) were effective. The molecular weight of the effective fractions from CNS was 100-200 daltons. Experiments of the effects of biogenic amines on the PSPS and the distribution of biogenic amines in CNS indicate that at least two neurohormones from the brain and the mesothoracic ganglion reciprocally control the elicitation of CS and provide an appropriate interval in the mating sequence of the male cricket. Octopamine and serotonin are possible candidates for these neurohormones (Fig. 1)<sup>2</sup>.

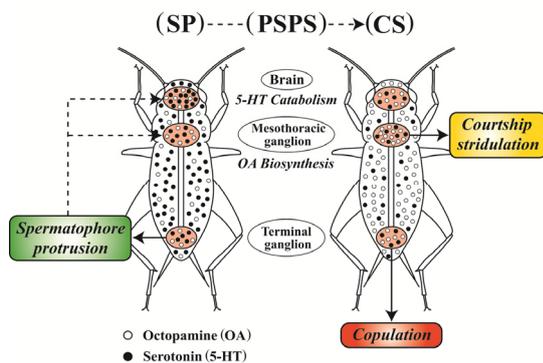


Fig. 1. Neurohormonal control of sexual behavior in male cricket. Distribution of octopamine and serotonin in CNS and hemolymph in SP and CS cricket.

### III. DEVELOPMENT OF SEXUAL BEHAVIOR

The mating sequences described above (courtship stridulation (CS), mounting, copulation (CP), and spermatophore protrusion (SP)) developed after eclosion (Fig. 2). Male crickets matured 3 days after eclosion. No mating behavior was displayed by the male on the day of eclosion. On the second day, about half the males showed SP, but few of them consummated the copulation. Many males transferred the day old spermatophore at CP on the next day. All females attracted matured males enough to elicit CS at the time of eclosion, but they could not mount or release CP from the male. Presumably, the female, on the day of eclosion, lacks the responses necessary for the male to proceed further with the sequence.

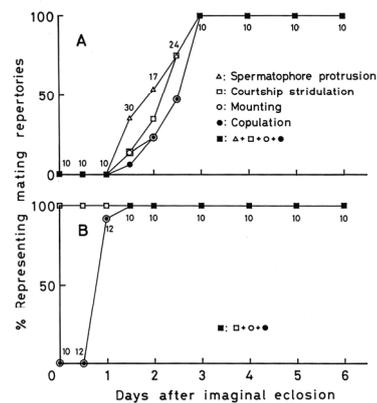


Fig. 2. Development of mating sequences after eclosion. (A) Elements displayed to mature females (7 days after eclosion). (B) Attractiveness of female measured by the behavior elicited from mature males (7 days after eclosion). Courtship stridulation (CS) refers to the number of animals showing CS after spermatophore protrusion (SP); mounting also implies preceding CS and SP; copulation implies a complete sequence. Numerals: number of insects observed.

### IV. AGGRESSIVE BEHAVIOR IN MALE CRICKET

Male crickets exhibit vigorous stereotyped aggressive behavior when they encounter conspecific males. They fight readily in almost any situation. Such fights vary in intensity, according to many factors, and in extreme cases can result in severe injuries and even death.

The crickets were kept in a controlled environment because body size is an important determinant of success in fights<sup>3</sup>. We provided 3 crowded groups and 2 isolated ones. Crowded group Ca was reared in a fivefold higher density than the other four groups. Group Cb had twice as many crickets as group Cc. Crickets were isolated in transparent or shielded cases. Isolation was achieved using the same volume of cases.

Crickets reared in the transparent cases were named Internet crickets, because they could see, hear and smell their congeners, but were unable to touch them. Hidden crickets could hear and smell their congeners, but were unable to see and touch them. Furthermore, we controlled the beginning of the isolation.

### V. EFFECTS OF GROWTH ENVIRONMENT ON INSTINCTIVE BEHAVIOR

#### A. Social Experience and Aggressive Behavior

In order to exclude the effects of body weight, we have analyzed the aggressive behavior of the male crickets whose ratio of body weight was less than 1.2. Observation was performed using the plastic arena with a base of 12 x 36 cm with 2 removable partitions. Single males were introduced into both side rooms and allowed to settle for 5 min. The partitions were then removed and the behavior of 2 crickets was observed for 5 min from their encounter.

In the fights between crowded crickets, most of them quickly exhibited dominance-subordinate interactions: gentle fights. On the other hand, in the fights between isolated

ones, prolonged intense fights were frequently observed. So, we scored the aggressiveness according to these criteria classified into 7 levels. In the fights between crowded crickets, the levels of aggressiveness of the winner were low.

In all fights most of Internet crickets won and the levels of aggressiveness were considerably higher. The greater part of Internet crickets that exhibited the highest aggressiveness continued to attack for more than one hour and finally killed their opponents<sup>4)</sup>.

### B. Development of Sexual Behavior and Aggression

We have examined both whether males attack females and whether males consummate copulation. Although crowded males never attacked females, the greater part of the Internet crickets attacked females with abnormal aggressiveness for 3 days after imaginal eclosion. The attacks on females of the Internet males extinguished 6 days after imaginal eclosion. Although partially isolated males in wire-mesh cases that allow tactile contact with other crowded animals also attacked females for 4.5 days after imaginal eclosion, their aggressiveness was not as high as that of Internet crickets (Fig. 3A).

#### Male's behavior against female

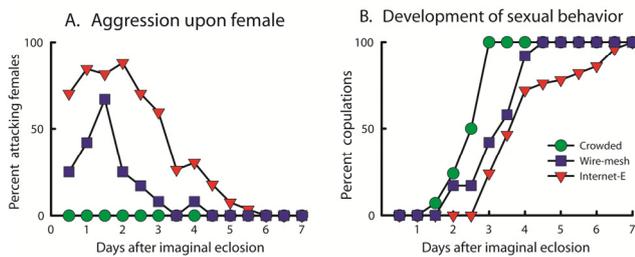


Fig. 3. Male's behavior against female after imaginal eclosion. (A) Daily changes of the percentage of individuals showing aggression upon matured females. (B) Daily development of the males' sexual behavior.

Normally the sexual behavior of the cricket develops after imaginal eclosion and adult male crickets exhibit stereotyped sexual behavior when they encounter females. Crowded males matured 3 days after imaginal eclosion, whereas partially isolated ones matured 4.5 days after and Internet males matured 6 days after<sup>5)</sup>(Fig. 3B).

The results indicate that the aggressiveness and the development of sexual behavior may be influenced by the social experience during larval stage. The aggressiveness and the duration of fights were dependent on the period of isolation. However, Internet crickets which had been isolated from an egg exhibited abnormal aggressiveness as compared with other isolated crickets. Therefore, it is probable that the presence or absence of tactile and/or visual communication plays an important role in the development of their aggressive and sexual behavior.

## VI. SOCIAL EXPERIENCE CONTROLS THE DEVELOPMENT OF INSTINCTIVE BEHAVIOR

Although lack of social experience delayed development of sexual behavior and aggressive behavior, either behavioral pattern was exhibited normally. As described in development of sexual behavior, it needs 3 days after imaginal eclosion for male to develop sexual behavior. Then, we examined the effects of isolation after imaginal eclosion on the behavior toward females in male Internet cricket. Isolation period after imaginal eclosion was changed and then males were encountered matured females every 12 hours.

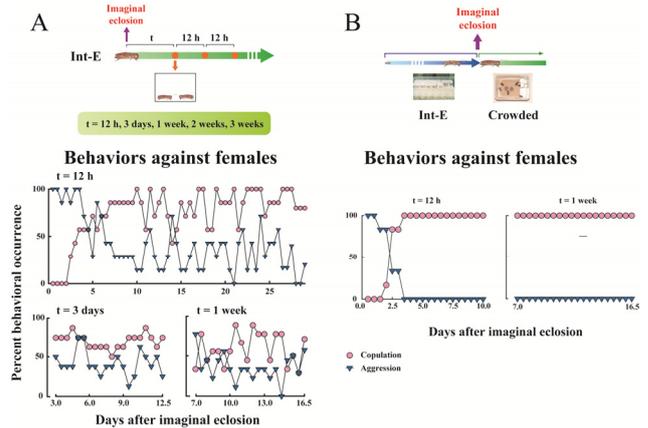


Fig. 4. Effects of isolation and social experience after imaginal eclosion on development of instinctive behavior in male Internet cricket. (A) Males were isolated fixed time just after imaginal eclosion. (B) Males were reared in crowded condition fixed time just after imaginal eclosion.

When males encounter females every 12 hours just after imaginal eclosion, rate of aggression upon females decreased as the time after imaginal eclosion was longer whereas rate of copulation increased. Males which were isolated continuously more than 3 days after imaginal eclosion exhibited similar pattern of behavioral selection toward females. Rate of copulation continued fluctuation and did not reach 100%. Furthermore, their aggression upon females did not extinguish<sup>6)</sup> (Fig. 4A).

Next, we examined the effects of social experience just after imaginal eclosion in male Internet crickets (Fig. 4B). When males were reared in crowded condition a half days after imaginal eclosion, they matured 3.5 days and then attack on females extinguished. However, every male reared in crowded condition 7 days accomplished copulation and they never attacked females (Fig. 4B).

Although isolation during larval stage make it disable that existence of female functions as a releaser of sexual behavior for male cricket, social experience after imaginal eclosion recovered the function. Then, crickets which were reared in crowded condition during larval stage isolated fixed time after imaginal eclosion, and development of sexual behavior and aggression upon female was investigated.

Although crowded males never attacked females (Fig. 3A), the greater part of crowded crickets which were isolated after imaginal eclosion showed aggression upon females and delay in development of sexual behavior (Fig. 5A). Furthermore, we examined males which were reared in crowded condition

all the time until a fixed time after imaginal eclosion. Males reared in crowded condition until 2 days after imaginal eclosion showed aggression upon females and delay in development of sexual behavior (Fig. 5B). Therefore, it seems likely that social experience immediately after imaginal eclosion is indispensable to development of sexual behavior.

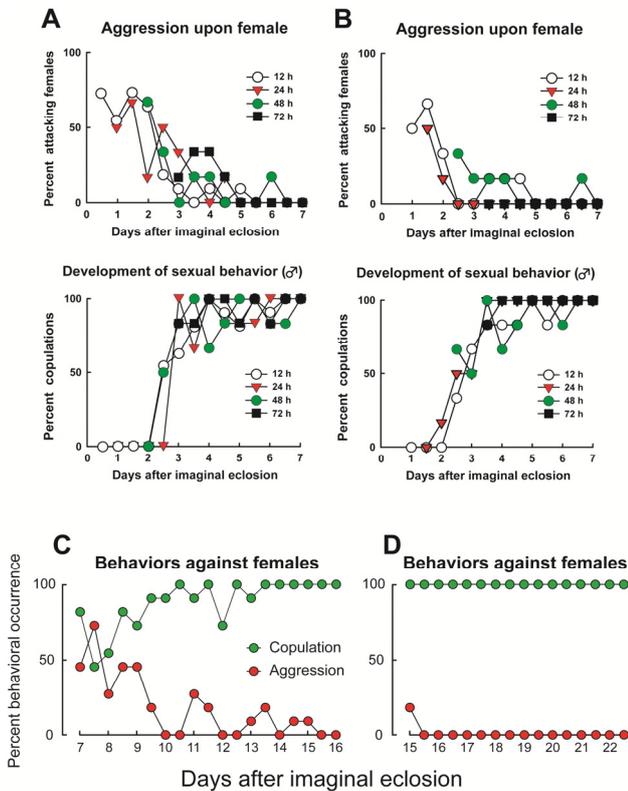


Fig. 5. Effects of isolation and social experience after imaginal eclosion on development of instinctive behavior in male crowded cricket. (A) Males were isolated fixed time after imaginal eclosion. (B) Males were reared in crowded condition fixed time after imaginal eclosion. (C) Males were isolated one week after imaginal eclosion. (D) Males were isolated 10 days after maturation.

## VII. CONCLUSION

Higher aggressiveness does not seem to induce attacking female, because isolated crickets except for Internet crickets those aggressiveness were not so high also attacked females in early encounters after imaginal eclosion. Any isolated male showed the reciprocal tendency of the development of sexual behavior as the percent of the aggression upon female decreased after imaginal eclosion. Thus, it seems likely that the male cricket has an internal mechanism which is concerned with the behavioral switching between sexual behavior and aggressive behavior.

Since the social experience for less than one week after imaginal eclosion recovers the delay of development of sexual behavior, it is hard to consider the innate program of sexual behavior collapsed by isolation.

Although basic composition of an instinct program is constructed under directions of the genes, it is probable that social experience contributes the composition of the

mechanism which detects a releaser, or the switching mechanism which is concerned with selection and decision of the behavior.

Development is a continuing process throughout which the animal is being tested by natural selection. At every stage the individual must behave in an adaptive manner if it is to survive. This may mean behaving quite differently from the adult for the young animal. The young animal is not just a small adult, nor is its behavior simply a preparation for adulthood. Development is a subtle process with many different interacting influences determining the way in which an animal behaves at each particular stage. Such influences may be external stimuli or internal events, such as the secretion of a hormone or the attainment of a particular stage of maturity; they may have rather generalized effects on much of the behavior of the animal or very specific ones on a single, small aspect.

Although our brain consists of about 100 billion neurons, the brain of a cricket consists of only tenth of thousands of neurons. Not only a cricket but insects were simplified instead of connecting a neuron intricately, and they succeeded in diversification of motivation by controlling a nervous system using hormonal system which functions effectively in the small body. By developing such an efficient hormonal system for the behavioral change, insects succeeded in stuffing the choice of many behaviors into the body of the limited size<sup>7,8)</sup>.

Crickets are never a social insect, however they fight between conspecific individuals over the limited resources and mate with their mates in order to produce their offspring. The behavior concerned with such self-maintenance and mating is inevitably realized under an interaction between individuals. When animals react to each other as individuals, rather than simply as members of the same species, they can be said to have a basic social relationship. The mechanism controlling the development of behavior through social experience is considered to be included also in the cricket as a common principle which guarantees the adaptability of behavior.

## REFERENCES

- [1] N. Tinbergen: The study of instinct, Clarendon Press, Oxford. (1951)
- [2] T. Nagao, T. Tanimura and T. Shimozawa: Neurohormonal control of the mating interval in the male cricket, *Gryllus bimaculatus* DeGeer, J. Comp. Physiol. A 168:159-164 (1991)
- [3] M. Iba, T. Nagao, and A. Urano: Effects of population density on growth, behavior and levels of biogenic amines in the cricket, *Gryllus bimaculatus*, Zool. Sci. 12:695-702 (1995)
- [4] T. Nagao, and S. Yamamoto: Effects of social experience on aggressiveness and development of the sexual behavior in male crickets, Comp. Biochem. Physiol. 124-A, S57:S38-5 (1999)
- [5] T. Nagao: Social experience contributes the development of instinctive behavior in male crickets, Zool. Sci. 21(12):1244-1245 (2004)
- [6] T. Nagao, A. Kishigami, K. Sasaki and Y. Tamori: Neurohormonal control of development and motivation of instinctive behavior in male crickets, Proc. 6th ABA Symp. 125-126 (2009)
- [7] T. Nagao, M. Hara and A. Kishigami: Male crickets accomplish copulation without courtship stridulation. Comp. Biochem. Physiol. 151B:21 (2008)
- [8] K. Sasaki, K. Yamasaki, K. Tsuchida and T. Nagao: Gonadotrophic effects of dopamine in isolated workers of the primitively eusocial wasp, *Polistes chinensis*. Naturwissenschaften 96:625-629 (2009)

# Mechanism of social adaptive foraging behavior in the honeybee

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**Abstract**—A honeybee informs her nestmates of the location of a flower that she has visited by a unique behavior called a “waggle dance.” We regard the waggle dance as a good model of the “propagation and sharing of knowledge” that maintains a society, and thus we are attempting to reveal the effects of the waggle dance in terms of the colony’s benefit using mathematical models and computer simulation based on parameters from observations of the bee behavior. From video analysis, we obtained necessary parameters such as bee’s locomotion pattern in the hive, the maximum walk distance, the location where bees performed the dance, properties of dance information, and behavioral patterns of followers. We, then, created a Markov model of bee foraging behavior and performed simulation experiments by incorporating those biological parameters. Our simulation faithfully expresses the actual bee behavior and showed that information transfer by the dance was important for the effective food collection. In parallel to biological experiments, we also developed a continuously automatic measuring system of environmental factors such as CO<sub>2</sub>, humidity, temperature etc and an automatic bee-tracking system by using a vector-quantization method. These will bring us better understanding of the effects of the waggle dance on the colony.

## I. INTRODUCTION

**H**IGHLY developed societies such as those of human beings require communication between individuals. The honeybee (*Apis mellifera*), one of the social insect species, is well known to have the ability to communicate with its nestmates, using the so-called “waggle dance” to inform them of the location of a food source (Fig. 1, [1]). In the waggle

dance, the dancer moves in a straight line with her wings beating (waggle run), then circles back to the starting point without wing-beating (the return run). On a vertical comb, the direction of the waggle run (during which the dancer wags her body from side to side and emits sounds) relative to gravity indicates the direction to the food source relative to the sun’s azimuth in the field. The duration of the waggle run depends on the distance to the food source. A few follower bees keep close contact with the dancer, and these bees may be recruited to visit the flower the dancer is locating for her nestmates (Fig. 1).

We regard the waggle dance as a good model of the “propagation and sharing of knowledge” that maintains a society, and are attempting to reveal the effect of the waggle dance in terms of its benefits to the colony using mathematical models and computer simulation based on parameters from observations of the bee behavior.

Past four years, we obtained necessary biological data from video analysis of honeybee behaviors and created a Markov model of bee foraging behavior based on our own biological data and literature. By using this model, we performed computer simulation experiments and found that waggle dance is advantageous for collecting food. In addition, we built a continuous data collection system for hive environments of inside/outside of the hive and developed an automatic tracking system for bee behavior in the hive. Some parts of results of these studies were already published [2-5]. Here we will review our results.

## II. RESULTS

### 2-1 Biological analysis of honeybee behavior

Behavioral studies were done in Sapporo from 8:30 am to 4 pm on several days between August and October, 2006 and 2007. Bee behavior on the vertical comb was monitored by a video camera and stored on a digital video tape (30 frames/sec), and then analyzed off-line frame by frame.

Video analysis revealed necessary parameters that are important for modeling and simulations of honeybee foraging behavior; (1) walk distance for 1 sec is less than 0.4 cm in about 80% of all walks (Fig. 2A) and there was a weak tendency that bees move forward in a short time (1 sec), (2) a bee performs the waggle run several times at one place on the comb and then moves to another place before resuming the waggle runs. The locations where waggle runs were observed appears to be clusters (Fig. 2B), (3) The orientation of the

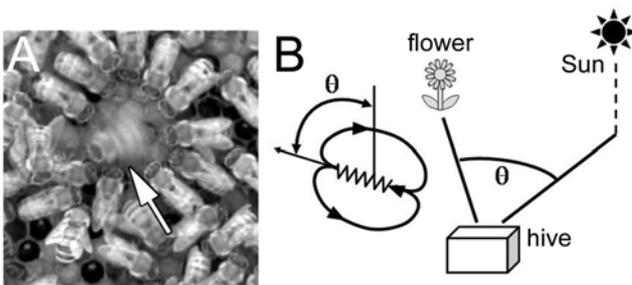


Fig. 1 Waggle dance (A) and the relationship between the dance orientation and food source (B).

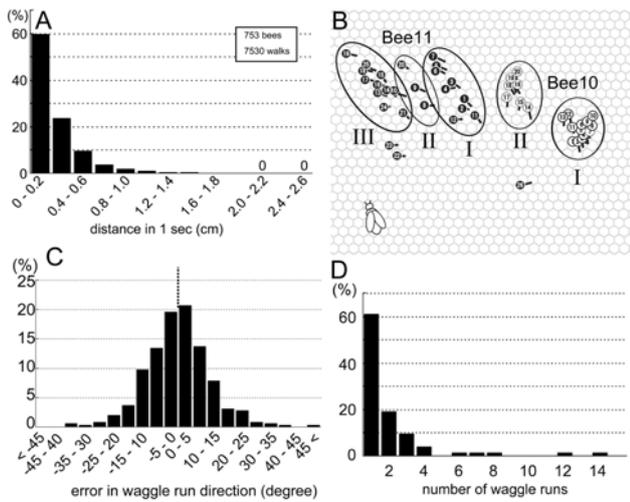


Fig. 2 Representative biological data we obtained for our model and simulation. A: Distribution of walk distances of bee in 1 s. Not so many bees walk in the hive. B: Locations of waggle runs. C: Distribution of the error of run angles. Angles of 84.9% of waggle runs differed from the mean orientation by  $\pm 15^\circ$ . D: The number of bees that followed waggle runs. Most of followers used to listen to dance one or two times.

waggle run varied from run to run even in a series of waggle runs performed by same the individual. It is found that angles of 84.9% of waggle runs differed from the mean orientation by  $\pm 15^\circ$  (Fig. 2C), (4) About 80% of followers turned away from the dancer after one or two sessions of waggle runs (Fig. 2D).

## 2-2 Model and simulations

We created a Markov model of bee foraging behavior by re-classifying bee behavioral states into eight categories: resting in the hive (resting), walking in the hive (wandering), flying for searching for a food source (scouting), success in finding a food source (exploiting), failure in finding a food source (returning), flying to a known food source (foraging), dancing, and following (Fig. 3). We created a mathematical model by incorporating the parameters obtained from our analysis and from studies in the literature.

By using this model, we performed simulation experiments. To validate our model, we first compare our simulation results with the results of the famous biological experiments with actual bees by Seeley et al. [6]. All the possible simulation conditions were prepared in the same way as in Seeley's experiment. The simulation results fit well with that of Seeley's (Fig. 4). We therefore concluded that our model and simulation reliably expressed the behavior of an actual bee colony.

Next, we examine the effect of the dance behavior on the foraging. We compared four virtual honeybee colonies: 1) bees that neither memorized the feeder locations nor performed a dance, 2) bees that memorized the location but did not perform a dance, 3) bees that memorized and danced

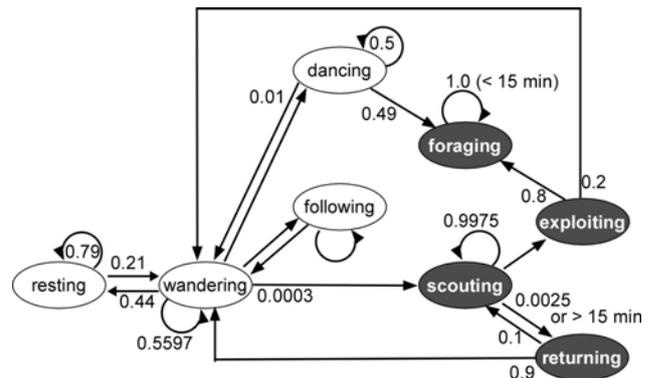


Fig. 3 The Markov model of bee foraging behavior.

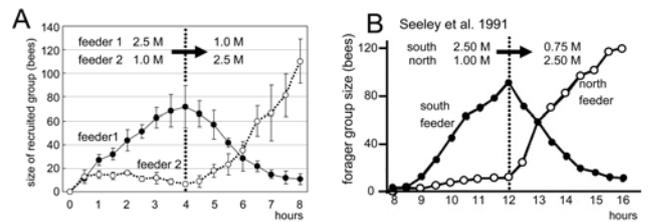


Fig. 4 The comparison of simulation experiments and biological experiments. Simulation results (A) well fit with Seeley's results (B).

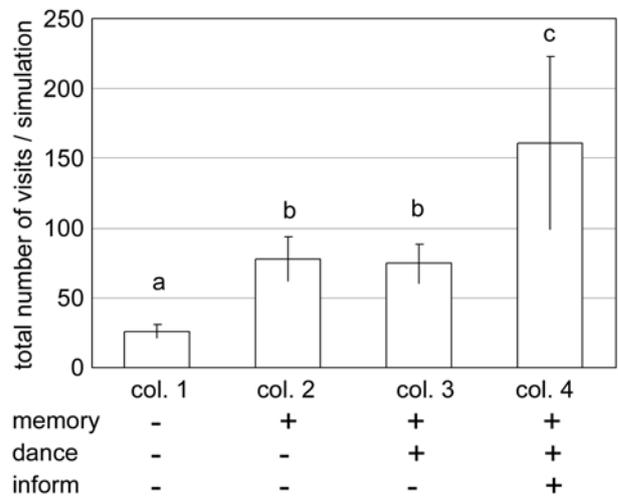


Fig. 5 Comparison of the four different types of honeybee colonies. The total number of visits in all feeders in one simulation was counted. Colony 4 clearly showed the greatest number of visits. Each bar indicates the mean  $\pm$  SD. Different letters denote significant differences ( $p < 0.01$ ).

but transferred random directional information about the feeder location, and 4) bees that memorized and danced with accurate information transmissions. The 10-time simulation exhibited that Colony 4 was significantly more successful in visiting feeders (Fig. 5). On the other hand, the smallest number of visits was found in Colony 1, suggesting that random searching is detrimental for food collection.

### 2-3 Carbon cycling of a honeybee colony under the environmental variation

Because the carbon flow is related with the weather and honeybee activities, the mathematical model of the carbon cycle in the honeybee colony based on the measured values is helpful for understanding the relationship between the colony energy budget and their social behaviors.

A two-frame observation hive with a queen was placed on a digital platform scale. Infrared cameras were set at the entrance of the hive for counting the number of honeybees getting in and out of the hive. CO<sub>2</sub> production of the colony was measured during closing the entrance and the ventilation holes by the computer controlled electromagnetic valves. The CO<sub>2</sub> concentration, temperature, humidity, and hive weight continuously logged into the computer (sampling intervals were 1 s for CO<sub>2</sub> and 5 min for the others). The number of bees in the whole hive was counted manually. Measurements were conducted on July 7-11, 2009 in University of Hyogo.

CO<sub>2</sub> production was measured during 5 min every 1 hour. Velocity of CO<sub>2</sub> increase,  $C$  (ppm s<sup>-1</sup>), was obtained as a gradient of a linear approximation of CO<sub>2</sub> concentration. The carbon outflow,  $C_{out}$  (g hr<sup>-1</sup>), was estimated by the following equation,

$$C_{out} = \frac{PV}{RT} \cdot C \cdot gC \cdot 10^{-6} \cdot 3600 \quad (1)$$

where  $P$  is the atmosphere pressure, 1 (atm),  $R$  is the gas constant, 0.082 (ℓ · atm · mol<sup>-1</sup> · K<sup>-1</sup>),  $gC$  is the weight of carbon, 12 (g),  $V$  is the volume of the hive, 19.5 (ℓ), and  $T$  (K) is the temperature in the hive.

In August 2008 and May 2009, we measured the number of foraging bees and the mean weight of the floral nectar and pollen that single foraging bees carried in a trip. From the results, the carbon inflow,  $C_{in}$ , was estimated as shown next,

$$C_{in} = N_{forage} \cdot Q_{nectar} \cdot P_{nectar} \cdot C_{nectar} + N_{forage} \cdot Q_{pollen} \cdot P_{pollen} \cdot C_{pollen} \quad (2)$$

where we assumed the ratio of the nectar ( $P_{nectar}$ ) and pollen ( $P_{pollen}$ ) foragers in all foragers ( $N_{forage}$ ) was 6:4. The carbon concentration of the nectar ( $C_{nectar}$ ) and the amount of carbon in the pollen ( $C_{pollen}$ ) were assumed 0.343 g g<sup>-1</sup> (equal to those of 40%-sucrose solution) and 30% of the mass of the pollen. In this study, the weight of the floral nectar ( $Q_{nectar}$ ) and pollen ( $Q_{pollen}$ ) carried in one foraging trip were estimated 40 mg and 10 mg, respectively.

The colony collected up to 3.59 g hr<sup>-1</sup> carbon in day time as the floral nectar and pollen by foraging activities (Fig. 6). The daily amount changed 8-15 g day<sup>-1</sup>. They emitted more than 0.66 g hr<sup>-1</sup> carbon as the respiration (Fig. 6). The total amount of the carbon outflow was more than 20 g day<sup>-1</sup>, meaning the colony could be losing its weight to consume the energy storage. The carbon budget in the colony estimated

from the difference between the carbon inflow by foraging and the outflow resulting from the respiration was 16.2-7.9 g day<sup>-1</sup>. We observed 40-80 g day<sup>-1</sup> of the weight loss during these days coincided with the total carbon flow.

It was also shown that the carbon dynamics in the colony were significantly correlated with the temperature, the humidity, and the CO<sub>2</sub> concentration inside and outside of the hive (Table 1).

Robust and adaptive properties realized by great numbers of small agents like a honeybee colony will lead to the future mechanisms of information and control systems.

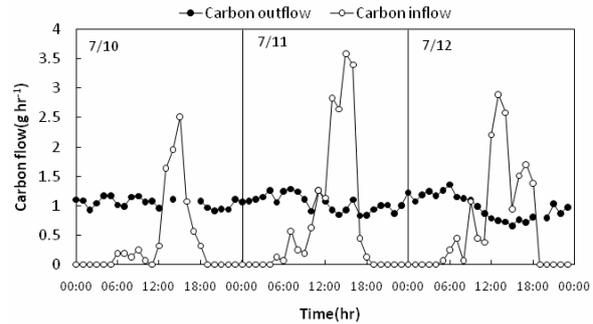


Fig. 6 Carbon flow in a honeybee hive. Black and white circles indicate carbon outflow and inflow, respectively. A peak of carbon inflow was found in the early afternoon every day.

TABLE 1 CORRELATION COEFFICIENTS BETWEEN CARBON FLOW AND ENVIRONMENTAL FACTORS.

	<b>C outflow</b>	<b>C inflow</b>	<b>C balance</b>
<b>Hive</b>			
Temperature	<i>-0.71</i>	<i>0.66</i>	<i>0.55</i>
Humidity	<i>0.74</i>	<i>-0.56</i>	<i>-0.44</i>
CO <sub>2</sub> conc.	<i>0.64</i>	<i>-0.60</i>	<i>-0.52</i>
<b>Control</b>			
Temperature	<i>-0.72</i>	<i>0.66</i>	<i>0.54</i>
Humidity	<i>0.45</i>	<i>-0.30</i>	<i>-0.22</i>
CO <sub>2</sub> conc.	<i>0.50</i>	-0.18	-0.08
<b>Difference of control and hive</b>			
Temperature	0.14	-0.02	0.03
Humidity	<i>0.72</i>	<i>-0.59</i>	<i>-0.47</i>

*Italicized values* mean the significant correlations ( $p < 0.05$ ).

### 2-4 Tracking system of multiple honeybees for behavioral analysis

It is important to know detailed movements of honeybees in a hive for revealing sociality of honeybees and to extract some parameters for modeling and simulating their behavior. We have been developing a tracking system of multiple honeybees for behavioral analysis by using the vector quantization method with an aim to extract necessary parameters quickly. Last year, we developed the system that could detect automatically and assign ID numbers to

individuals. By using this system, we obtained trajectories of each honeybee from a temporal sequence of their location information. In the experiment, more than 500 bees were detected automatically and trajectories of about 350 individuals were obtained.

We improved this system available for behavioral analysis. Behavioral analyses require not only visual observation of bee behavior but also numeric information such as location, walking velocity and direction, and travel distance of each bee. The distance  $l_i$  is obtained from the following equation after calculation of the location of a bee,

$$l_i = \sum_{t=s_i}^{e_i-\Delta t} |p_i(t + \Delta t) - p_i(t)| \quad .$$

Where  $p_i(t) (= (x_i(t), y_i(t)))$  is the location of a bee  $i$  at time  $t$ , when  $x_i(t)$  and  $y_i(t)$  are the locations of this bee described by the x- and y-axis, respectively.  $t$  is unit time, and  $s_i$  and  $e_i$  are the starting and ending time of the tracking of this bee, respectively. The direction,  $\theta_i(t)$ , is obtained by the following equation,

$$\theta_i(t) = \arctan \frac{y_i(t + \Delta t) - y_i(t)}{x_i(t + \Delta t) - x_i(t)} \quad .$$

By applying our system to a 100-second movie (720 x 480 pixels, 30 fps) of a hive ( $\Delta t = 1$  s), the travel distances and directions every 10 seconds were calculated. We found that

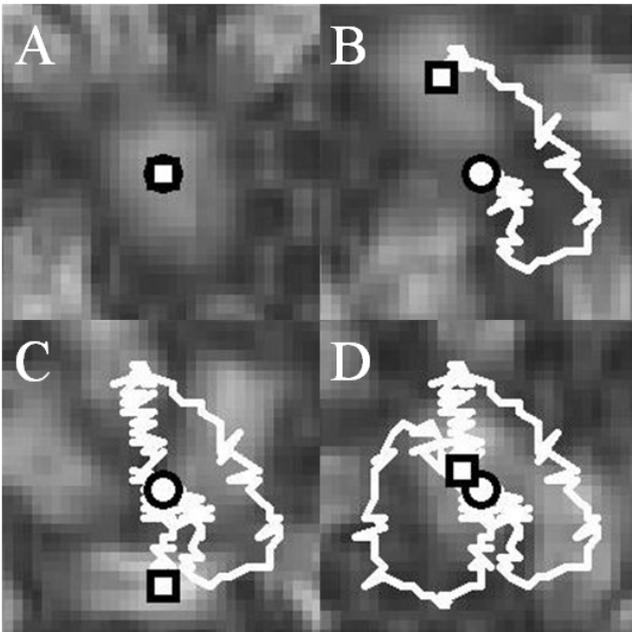


Fig. 7 Detection of a waggle dance. The path of a walking honeybee showed the figure of eight. The circle and square indicate the starting and the current point, respectively. The temporal sequence of images corresponds with an alphabetic order.

most of bees moved less than 15mm during 10 s and toward the upper left. We strongly believe that this system become a powerful tool for behavioral analysis especially detection of particular movements such as a waggle dance.

### III. FUTURE PLAN

The followings are our main achievements past four years. 1) from behavioral analysis, we found for example that bee's dance contains a substantial margin of error in information and that most follower bees turned away from dancers after one or two consecutive sessions of attendances of dances [2, 3], 2) we created a mathematical model of bee foraging behavior and simulations showed that dance behavior was beneficial for collecting food [3, 4], 3) we developed continuously automatic measuring system of hive environments [5], 4) we developed an automatic detection system of bee movements in the hive.

Although our research indicated that honeybees achieve efficient forages by dance behavior, it is expected that the probability of the failure foraging is high because of the small number of chance to listen to such dance information as "ambiguous" information about the location of the food source. However, even if the number of listening of each individual is small, the colony itself would obtain averaged information, if the number of honeybees that fly out for foraging is large. Bee colonies may overcome this problem caused from impression information in this manner. This possibility is an opposite direction of the design for engineering products that are never allowed to fail.

Finally, we believe that our research is not merely a topic for biology, and that the mechanisms for maintaining a society by the sharing of information will have useful applications to practical utility such as optimization and control of robots under a multi-agent environment.

### IV. REFERENCES

- [1] K. von Frisch, *The dance language and orientation of bee*. Harvard University Press, Cambridge, Massachusetts, London, 1993
- [2] R. Okada, H. Ikeno, N. Sasayama, H. Aonuma, D. Kurabayashi, and E. Ito "The dance of the honeybee: how do honeybees dance to transfer food information effectively?", *Acta Biol Hung*, vol. 59 (suppl), pp. 157-162, 2008
- [3] R. Okada, H. Ikeno, H. Aonuma, and E. Ito "Biological insights into robotics: honeybee foraging behavior by waggle dance", *Adv Robotics* vol. 22, pp. 1665-1681, 2008.
- [4] R. Okada, H. Ikeno, T. Kimura, M. Ohashi, H. Aonuma, and E. Ito. "Markov Model of Honeybee Social Behavior", *Information in press*, 2010.
- [5] M. Ohashi, R. Okada, T. Kimura, and H. Ikeno "Observation system for the control of the hive environment by the honeybee (*Apis mellifera*)", *Behav Res Methods*, vol. 41, pp 782-786, 2009.
- [6] T.D. Seeley, S. Camazine, and J. Sneyd. "Collective decision-making in honey bees: how colonies choose among nectar sources", *Behav. Ecol. Sociobiol.*, vol. 28, pp. 277-290, 1991

# Social Context Modulates Network Structure of Lateral Frontal Cortex in Primates

Kazuhiro Takenaka, Toru Yanagawa, Yasuo Nagasaka, Naotaka Fujii

**Abstract**—We aimed to develop novel approach to describe social brain function by modulation of neural network structure. We recorded neural activity from Japanese macaque by using electrocorticogram (ECoG) array implanted on lateral frontal cortex and applied Granger Causality (GC) analysis to measure causal relationship between regions. The analysis showed that causal relationship from prefrontal cortex and premotor cortex to frontal eye field was suppressed when human competitor sat next to the macaque regardless of hierarchical conditions. The findings suggest that the method is useful for describing complex neural functions in terms of network relationship between brain regions.

## I. INTRODUCTION

Human beings are extremely social animal. We can make socially correct behavior that is regulated by social rules. Social rules are mostly tacit and changing continuously depending on social context at the moment. Scientists, especially ethologists and psychologist, have tried to understand mechanism of adaptive social behavior for long decades, however, it is not clearly understood yet in neuroscience. It is because there were huge technical limitations in experimental setup to learn neural mechanism of adaptive social behavior, which is called social brain function, since the function emerges only in realistic and unpredictable social environment.

In previous experimental setup in neuroscience, experimenter designed specific task that strictly manipulated behavioral and environmental parameters to address specific questions based on specific hypothesis. However, under such experimental setup, almost everything was predictable. The setup was suitable to reveal contribution of each of the parameters to neural modulation under the condition, but the results obtained from different experiments were not easily comparable and transferable, because task designs were different. Therefore, conventional experimental methods were not applicable to reveal social brain mechanism, because adaptive social behavior can be observed only when social condition shifts, so that we needed to develop new task design to tackle social brain functions.

On the other hand, there was limitation in neural recording technique to understand the function. It is commonly thought that multiple neural networks in brain achieve social brain function, because the function has to evaluate different types of complex environmental parameters and understand current social context for adaptive behavioral selection. However,

there was almost no recording method that allows recording neural activity from multiple brain regions with enough temporal and spatial resolutions. fMRI can record neural activity from whole brain but temporal resolution was not high enough and behavioral limitation was high because subject has to be fixed and socially isolated in scanner. EEG has good temporal resolution but spatial resolution was low and behavior was also limited because of low S/N ratio due to subject's motion. Invasive single cell recording has high temporal and spatial resolutions and allows relatively free behavior but can't cover wider brain regions. Thus, for revealing neural mechanism of social adaptive behavior, novel recording technique, which allows recording from multiple brain regions under free behavioral condition with high temporal and spatial resolutions, was required.

Task design and recording method are not the only issue when revealing social brain mechanism, there is one more problem that is analytical method. If we could record neural activity from whole brain under realistic social environment while subjects were making adaptive social behavior, we still don't know appropriate analytical method how to correlated neural activity with behavior, because there are numerous amounts of parameters that are continuously changing and interacting each other. In other words, we need novel analytical method to understand social adaptive mechanism from gigantic multi-dimensional dataset consists of complex environmental, behavioral and neural data.

To solve these problems, we developed novel recording technique that is called multi-dimensional recording (MDR) technique, which combines motion capture system, video cameras, eye tracking system and chronic multi-electrode recording method [1][2]. In MDR setup, subjects can behave freely without physical restraint. Their behavior is monitored and recorded by motion capture system and can be analyzed later with neural activity. Neural activity is recorded by multi-electrode array that is chronically implanted in wide areas of brain. Subject is cabled during recording but behavioral restraint due to the cable is minimal compared to conventional recording methods so that we can record and analyze subjects' social behavior while they are interacting each other.

While developing MDR technique, we did preliminary studies that revealed contribution of prefrontal and parietal cortex during social adaptive behavior depending on social hierarchy in monkeys. In the preliminary studies, we used conventional multi electrodes to record neural activity that could cover only limited brain regions by which we could not analyze network interactions between multiple brain regions,

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because information carried by single cell was too sparse.

Here we introduced new electrode, ECoG (electrocorticogram), to solve the problem. In this experiment, we implanted ECoG electrodes that covered left lateral frontal cortex continuously from prefrontal cortex to parietal cortex with 3.5mm spacing and applied newly developed analytical method to reveal social brain function at network level.

## II. METHOD

### A. Recording

We recorded neural activity simultaneously from multiple brain regions by using ECoG electrode. We placed 64ch electrode array on the left lateral frontal cortex of a Japanese macaque covering from the prefrontal cortex to the parietal cortex (Fig.1). Sampling rate of the recording was 1042Hz. Monkey's behavior during behavioral task was recorded by optical motion capture system.

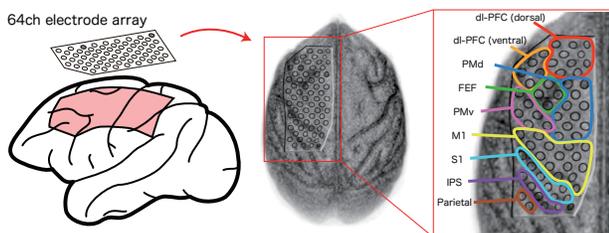


Fig. 1. ECoG array position

### B. Task

During the task, we placed a piece of food on a table. Monkey could take the food if he wish. We applied three social conditions that could alternate monkey's food taking behavior (Fig.2). In the first condition, there was no competitor so that monkey could take reward without hesitation (Monkey-Alone condition). In the second condition, there was human competitor sitting next to monkey. in this condition, human competitor behaved as submissive so that monkey could take reward without hesitation (Monkey-High condition). In the third condition, everything was the same as Monkey-High condition except human competitor behaved as dominant (Monkey-Low condition). In this condition, monkey tended to suppress food-taking behavior when food was placed in competitive space. In latter two conditions, human competitor sat either left or right to monkey that changed location of conflict space.

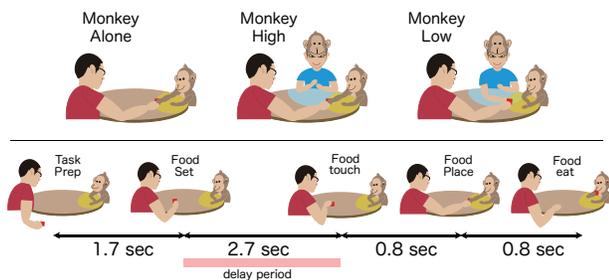


Fig. 2. Social Condition Task

### C. Analysis

To describe network relationship between multiple brain regions, we introduced a statistical index calculated by causal analysis called Granger Causality (GC) [3]. GC index was calculated based on prediction error using auto-regressive (AR) model. Let's suppose that there are two time-series datasets,  $\{x_t\}$  and  $\{y_t\}$ . First, we make one AR model that will predict value of data at  $x_{t+1}$  by using own past history of  $\{x_t\}$  (Eq.1). Second, we make another AR model that will predict value of  $x_{t+1}$  by using histories of  $\{x_t\}$  and  $\{y_t\}$  (Eq.2). If these two prediction error  $\epsilon_t^x$  and  $\epsilon_t^{x|y}$  are different, it means that  $\{y_t\}$  influences to  $\{x_t\}$ . In GC analysis, we took the difference of prediction error as index of causal relationship (Eq.3).

$$x_{t+1} = A \cdot X_t^{(m)} + \epsilon_t^x \quad (1)$$

$$x_{t+1} = B \cdot X_t^{(m)} + C \cdot Y_t^{(m)} + \epsilon_t^{x|y} \quad (2)$$

$$GC = \log(\text{Var}(\epsilon_t^x)) - \log(\text{Var}(\epsilon_t^{x|y})) \quad (3)$$

In these equations,  $m$  is a temporal length of past history of  $\{x_t\}$  and  $\{y_t\}$  used for prediction.  $(X_t^{(m)} = (x_t, x_{t-1}, \dots, x_{t-m})^t)$ . To determine  $m$ , we first calculated Akaike's Information Criterion (AIC) and found that AIC decreased rapidly while  $m$  was increased up to 4 but later AIC decreased slowly and reached closer to the least value when  $m$  was over 5. Therefore, we determined parameter  $m$  as 10 that is more than twice of 4.

Since it is obvious from the definition of GC index explained above, GC analysis can tell direction of information as well as amount of information flow between two time-series. GC index from electrode A to electrode B is different from GC index from electrode B to electrode A. Due to the feature, GC is different from other relationship index like correlation coefficient.

In traditional GC analysis, it assumes that these time-series data are stationary. However, neural activity and network structure are non stationary and change dynamically depending on context. Therefore, we applied GC analysis with sliding window [4]. The window size was 500 samples and the window was moved with 100 samples step.

## III. RESULT

We used one Japanese macaque for the experiments. Monkey performed reaching task width three social conditions. We recorded neural and behavioral activity during performance of 240 trials for each condition.

During the task performance, we occasionally manipulated task parameters: the food position (left or right), the existence of competitor and the relative position of monkey and competitor (left or right). Though these manipulations, we expected we might be able to detect social context dependent modulation in neural activity. To investigate the effects of social conditions, we mainly focused on the activity during delay period, in which influence of motion planning or reward prediction on neural activity was minimal, because location of food placement was not decided yet at that period.

### A. Behavior

Monkey did not hesitate to take food both in Monkey-Alone and Monkey-High conditions. In Monkey-Low conditions, monkey suppressed food-taking behavior when food was placed at conflict space but did not show suppression when food was placed in non-conflict space. In all conditions, we did not find difference in motion velocity.

### B. Event Related Potential

We aligned normalized value of recorded activity by the end of the delay period to find rough trend in the delay period. Fig.3-A shows trend and Fig.3-B shows significance probability of t-test to evaluate difference in activity between two conditions such as Monkey-Alone and Monkey-High condition. These figures show that there was a period in which specific electrodes were activated around 1 second after the end of the delay period. However, the activation pattern was not modulated by social conditions. On the other hand, there was no specific activation pattern in the delay period.

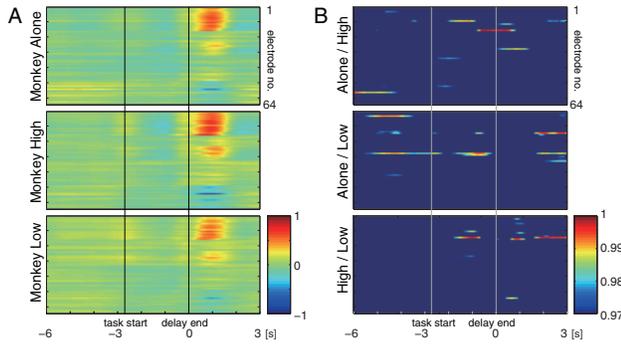


Fig. 3. Event Related Potential

### C. Granger Causality

We calculated Granger Causality (GC) index with sliding window in all electrode pairs to measure amount of information flow between two brain regions. First, we plotted mean of GC index in the delay period. Top three figures in Fig.4 are matrices that show mean of GC index in the delay period with three different social conditions. The figures show that there was specific pattern of GC index for each social condition. Lower three figures in Fig.4 are matrices that indicate absolute value of difference between two means of GC index shown above. The figures show that GC index between only particular pairs was modulated by existence of competitor regardless of hierarchical conditions.

GC index from electrode 6 (dorsal Prefrontal Cortex:PFCd) to electrode 21 (dorsal Premotor Cortex:PMd) differed significantly by changing social condition. Fig.5 is probabilistic distribution of GC index from electrode 6 to 21 in the delay period. Left figure shows histogram (probabilistic distribution function), center figure shows median and quartile, right figure shows cumulative distribution function (CDF). Three figures, especially CDF, show that GC index in Monkey-Alone condition was larger than in other conditions,

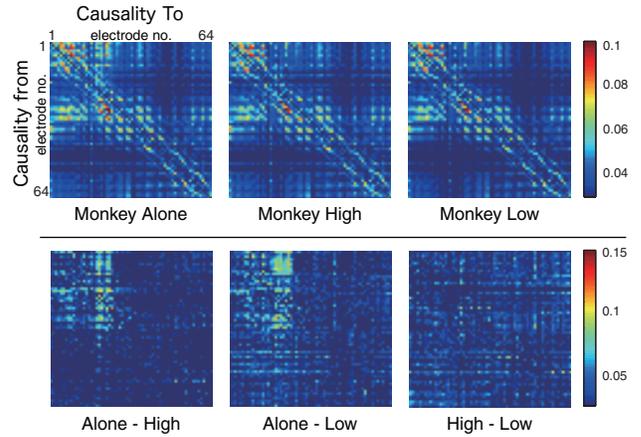


Fig. 4. GC matrix between electrode

and there was no difference in GC indexes between Monkey-High and Monkey-Low conditions.

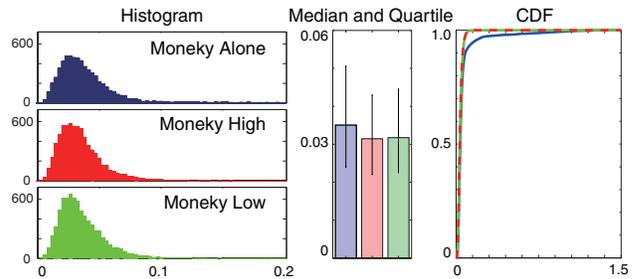


Fig. 5. GC distribution from Elec.6 to Elec.21

Modulations of GC index seem to share same tendency in each brain regions (Fig.4). So, we calculated average of GC indices for each brain regions shown in Fig.1. Fig.6 is the matrices of the averaged GC indices and the difference of the average for each condition. The figure shows that GC index “from PFCd to FEF” and “from PMd to FEF” in Monkey-Alone condition was significantly lower than in competitor present conditions (Monkey-High and Monkey-Low condition).

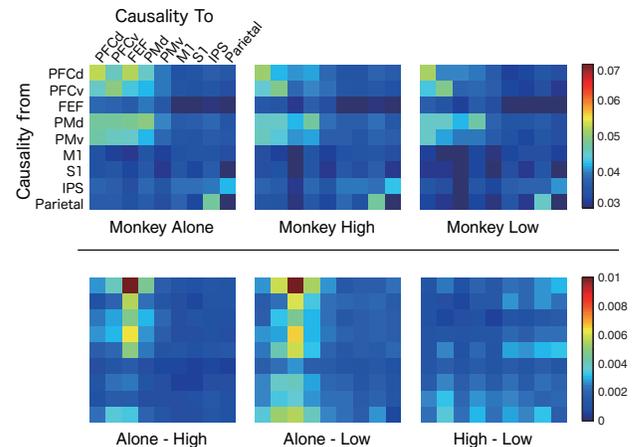


Fig. 6. GC matrix between region

Then, we plotted GC index aligned by the end of the delay period in the same format as Fig.3 to see dynamic

modulation of causal relationship. However, GC index had many dimension ( $64 \times (64-1) = 4032$ ) so that we plotted GC index of only selected regions, specifically from PFCd to other regions (Fig.7) and from other regions to FEF (Fig.8). These figures show that particular GC indexes, especially from PFCd to FEF and from PMd to FEF was different between Monkey-Alone condition and the competitor present conditions. Moreover, the specific causal relationship from other regions to FEF was observed continuously in the delay period, and disappeared after the end of the delay period.

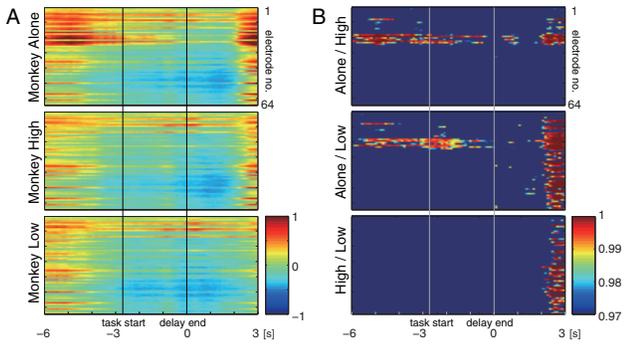


Fig. 7. GC time-series from PFCd

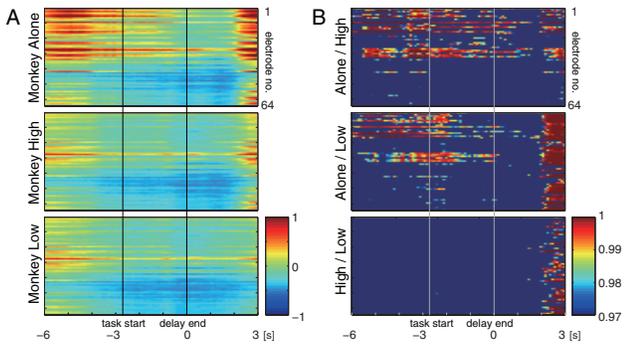


Fig. 8. GC time-series into FEF

#### D. Causal Network

We depicted causal network structure in the brain by using GC index between brain regions. Fig.9 shows causal network structure during the delay period in which arrow indicates existence of significant causal relationship. Left figure is the structure during Monkey-Alone condition, and right figure is the structure during Monkey-High and Low condition. This figure shows that there were general causal relationships unaffected by social condition among PFCd, PFCv, PMd and PMv. On the other hand, the relationship from PFCd and PMd to FEF was modulated by social condition.

### IV. CONCLUSION AND FUTURE WORKS

#### A. Conclusion

We found differences in neural signal during different social conditions not at raw activity level but at network activity level described by causal relationship between two regions. Social condition dependent modulation in GC index was observed in causal relationship from PFCd and PMd

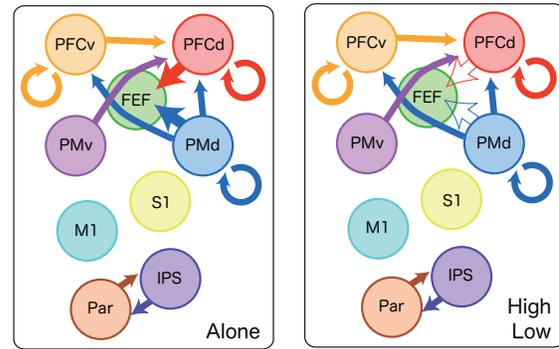


Fig. 9. Granger Causal network in delay period

to FEF. It means that the modulation of causal relationship occurred only in particular regions. Moreover, we also found that location of competitor, either right or left, did matter on the modulation but monkey's hierarchical context did not matter. It was interesting because behavioral output during Monkey-High and Monkey-Low condition were totally different, which suggests that existence of other, regardless of high or low condition, could induce modulation of functional network structure in the brain.

Although, causal network structure was altered when social condition was switched from non-social condition (Alone) to social conditions (High and Low), raw level activity did not change. How could it happen? We would like to propose it could be made by participation of other brain regions that could establish new network structure, which might be exclusively used for social condition.

#### B. Future Works

We recorded neural activity simultaneously from multiple brain regions by using ECoG and found modulation in causal network structure. However, the area covered by ECoG was still limited. For the next step, we would like to record neural activity from larger cortical and subcortical area simultaneously. Then, we might be able to reveal how whole brain network structure would change depending on social context.

In this experiment, we only focused on the effect of existence of other in network structure. However, there must be other conditional parameters in social environment that will influence the network structure. Finding those parameters are difficult especially when those parameters are interacting. Thus, we need to develop novel way to extract effective parameters automatically that may contribute to neural modulation in causal network structure.

### REFERENCES

- [1] N. Fujii, S. Hihara, and A. Iriki, "Dynamic Social Adaptation of Motion-Related Neurons in Primate Parietal Cortex," *PLoS ONE*, vol.2, no.4, e397, 2007.
- [2] N. Fujii, S. Hihara, and A. Iriki, "Social cognition in premotor and parietal cortex," *Social neuroscience*, vol.3, no.3-4, pp.250-260, 2008.
- [3] C.W.J. Granger, "Investigating causal relationships by econometric models and cross-spectral methods," *Econometrica*, vol.37, no.3, 1969, pp 424-438.
- [4] Y. Zhang, Y. Chen, S.L. Bressler and M. Ding, "Response preparation and inhibition: The role of the cortical sensorimotor beta rhythm," *Neuroscience*, vol.156, no.1, pp 238-246, 2008.

# GroupD : Common Principle of Mobiligence

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## 1. INTRODUCTION

A common principle of Mobiligence observed in various living things is considered in Group D. To do so, we should explain the principle as objective as possible. That is, we try to express various phenomena in living thing by mathematical or physical way. Now, some hypotheses are going to propose in Group D. Multi-Layer, Multi-Feedback, Multi-Optimality of Prediction Mechanism are the examples. We expect that one of the common principles of Mobiligence is understood if these are expressible unitedly in the word of the mathematic. In this note, we report the results in Group D in 2009. Concretely, we propose a concept of implicit control and Explicit control as a candidate of common principle of structure of Mobiligence. See Fig.1.

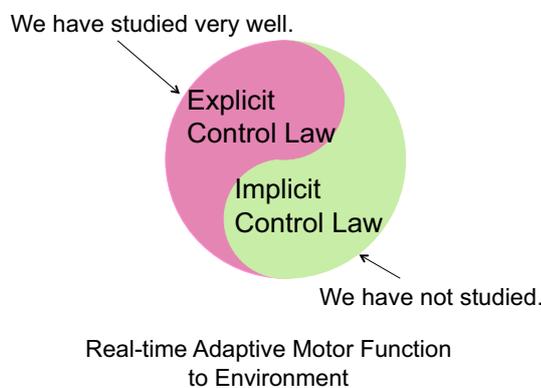


Fig.1 Dual-Structure of Mobiligence

## 2.STRUCTURE OF GROUP D

In Fig.2, we show the hypothesis in Group D and the relation between each hypothesis and the member of Group D.

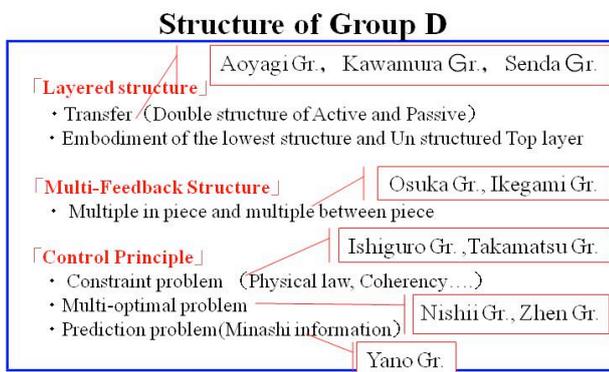


Fig.1 Structure of Mobiligence, and research allotment

- D01-01 Voluntary movements controlled by “Mi-Nashi” created in the motor cortices (Leader:Masafumi Yano, Tohoku University)
- D01-02 Discovery and development of dynamical common principle of mobiligence (Leader: Koichi Osuka, Kobe University)

D01-03 Understanding Mobiligence from Coupled Oscillators with Simple Motile Function (Leader: Akio Ishiguro, Tohoku University)

D01-11 Studying autonomous robots and explorative behaviors of flies to understand biological autonomy (Leader: Takashi Ikegami, The University of Tokyo)

D01-12 Emergence of mobiligence by environment- generation in flapping flight of butterfly (Leader: Kei Senda, Kyoto University)

D01-13 A study on adaptation to environments in a network of dynamical elements (Leader: Toshio Aoyagi, Kyoto University)

D01-14 Basic strategy for trajectory planning in living movements (Leader: Jun Nishii, Yamaguchi University)

D01-15 Adaptive behavior and emergence of biological function by environment dependent tube networks in plasmodial slime mold (Leader: Atsuko Takamatsu, Waseda University)

D01-16 Measurement and Modeling of Human Movement Mastery Process ( Leader: Sadao Kawamura, Ritsumei- kan University)

## 3. HYPOTHESIS OF COMMON PRINCIPLE

In this chapter, we introduce a candidate of common principle of Mobiligence produced by integration of the researches of the members of Group D.

At first, to understand a principle of design of Mobiligence, we have to understand a principle of design of control system of living things. However, if we try to draw a block diagram of control system of living things, some problems appear. The most essential problem is the problem called indivisible. That is, we can not separate the control system of living things into control object, control law and environment. Therefore, the following block diagram can be obtained. See Fig.3.

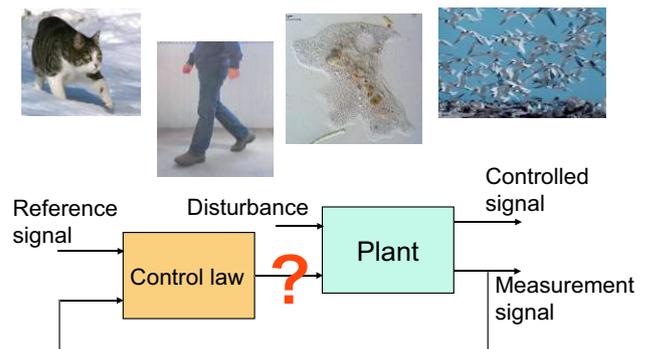


Fig.3 Block diagram of control system of living things

For example, we can see that the following properties belong to the system of living thing.

[Indivisible system] Border of plant, control law and field are not clear.

[Non-stationary system] Border of plant, control law and field are not fixed.

[Self-reference system] Biological system can produce reference trajectory by itself.

[Self-energy-generating system] Biological system has

energy source inside the body.

These are the properties that are not seen in most artificial control system. We think that the most essential property in the above four is Indivisibility( Indivisibility system). In other words, once we could treat this property well, then we can expect that the other properties can be treated properly too. Here, we define the problem, which find a method for treating the indivisibility well, as Problem of Indivisibility.

You must define some terms definitely so that such argument development does not become uncertain. And to do so, let us start to assume the existence of "a subject which attentions to the object and its will". Although we omit a detail discussion on this point, if we consider some artificial object, then the subject is a human. Or, if we focus on living things, the subject is an analyzer who is interested in the living things. In case of mammals, depending on the level which are considered, we can regard the upper part of the brain as the subject.

According to the preparations, let us define "Environment:  $E$ " as the whole world. In the environment, we assume that there exists a kind of "Will ( or motion task ):  $T$ " and an Object which is considered to move. Here, we call the object as "Plant : $P$ ". See the equation.

$$P=\mathcal{P}(T) \quad (1)$$

In this note, we take a standpoint where the control object is born only after there is  $T$ .

We define "Field : $F$ " as the following. (a) Field  $F$  is a part of environment  $E$  and includes plant  $P$ . (b) Field  $F$  is a set which works so as to help the will  $T$ . Although, the environment  $E$  exists regardless of the subject or the attention, the field  $F$  will be decided the existence depends on existence / non-existence of the will  $T$  or the plant  $P$ . We think that, even if the field  $F$  exists physically, the field  $F$  appears or disappears depends on the will  $T$ . That is

$$F=\mathcal{F}(E,T,P). \quad (2)$$

The amount of contribution of  $T$  and  $P$  in the above equation depends on the situation. Of course, the field  $F$  changes with the change of the environment  $E$ .

Next, in the situation where the will  $T$ , the field  $F$  and the plant  $P$  exist, let us call a factor as Control law : $C$ , if it works so as to move the plant according to the will  $T$ . That is,

$$C=\mathcal{C}(E,T,P). \quad (3)$$

Finally, we call the whole system including the field  $F$ , the plant  $P$  and the control law  $C$  as Control system:  $S$ . That is,

$$S=\mathcal{S}(F,P,C). \quad (4)$$

Under the above preparations, we propose an answer to the indivisible problem. The point is that we introduce the 4<sup>th</sup> element among the three elements ( plant  $P$ , control law  $C$  and field  $F$ ). We named the 4<sup>th</sup> element as "Implicit Control Law  $C_I$ ". We call an element of control law in ordinal sense as "Explicit Control Law  $C_X$ ". That is, the control law consists of Implicit Control Law and Explicit Control Law. See the equation below.

$$C = C_X \oplus C_I \quad (5)$$

Where, the operation  $A \oplus B$  stands for composition of the element  $A$  and the element  $B$ . Furthermore, we regard the Implicit Control Law consists with the following three parts. See Fig.4.

$$C_I = C_F \oplus C_P \oplus C_{FP} \quad (6)$$

Where,

$C_F$  :Field dependent Sub-Implicit Control Law,

$C_P$  :Plant dependent Sub-Implicit Control Law,

$C_{FP}$  :Plant and Field dependent Sub-Implicit Control Law.

Thus, the following "summary" is obtained..

- The Sub-Implicit Control Law  $C_{FP}$  is the implicit control law, which is appeared by the interaction of field  $F$  and plant  $P$ . And, this is induced by the feedback structure constructed between plant and field. We call this feedback structure "Implicit Feedback structure".
- The Sub-Implicit Control Law  $C_{FP}$  disappear with disappearing the interaction of field  $F$  and plant  $P$ .
- The Sub-Implicit Control Law  $C_{FP}$  changes in real-time according to real-time variation of the field  $F$ .

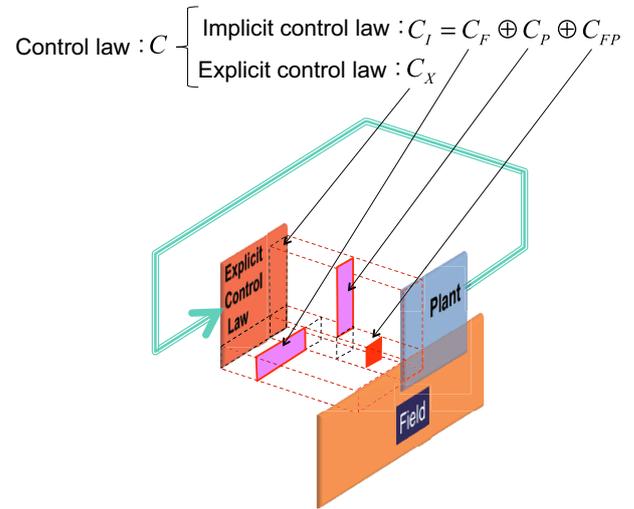


Fig.4 Structure of Mobiligence

From these discussion we have the conclusion of this paper.

Conclusion: Real-time Environmental Adaptation Function: We understand the real-time environmental adaptation function Mobiligence of the living thing as the following.

[Existence] The real-time environmental adaptation function of the living thing come from the Sub-Implicit Control Law  $C_{FP}$ .

[Function] The function of the real-time adaptation of the living thing is a function which adjusts the Explicit Control Law  $C_F$  so as to utilize the characteristics of Implicit Control Law  $C_{FP}$  efficiency. See Fig.4.

[Understanding] To understand the real-time adaptive ability of the living things, we have to know both Explicit Control Law  $C_X$  and Implicit Control Law  $C_I$  simultaneously. Especially, because the Implicit Control Law never exists outside the Field, if you take the living thing out of the field and put it in your laboratory, you never understand the real-time adaptive ability. Of course, in this case, you can understand the ability of the Explicit Control Law  $C_X$ . But this does not mean that you can understand the whole ability which we want to know. See Fig.1.

## 4.CONCLUSION

In this note, we introduced a candidate of common structure of Mobiligence. This structure is produced by integration of the results of the members of Group D. At this stage, our main result is the following. That is, Mobiligence has the dual structure such kind of Implicit Control and Explicit Control.

# Voluntary Movements Controlled by "Mi-Nashi" Created in the Motor Cortices.

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## I. INTRODUCTION

A voluntary movement is an action that the biological system makes for carrying out an aim with adapting unpredictable environments. The aim of the movement can be acquired by the system having "Mi-Nashi". As a higher constraint for resolving the ill-posedness in motor control, "Mi-Nashi" has to set practical constraints in various levels of control mechanisms in real time. Furthermore, for adapting unpredictable changes in conditions of the system and the environment, "Mi-Nashi" should emerge from the system itself depending on interactions between the system and the environment, and the system have to evaluate whether the emerged "Mi-Nashi" would be satisfied every moments. These are computational problems that the motor control system, i.e., the motor cortices, has to solve during the voluntary movement control in the real world. From April 2005 to March 2010, we addressed the following issues: modeling the bipedal walking system; modeling control mechanisms for arm movements in unpredictable environment; psychophysical analysis of human arm reaching movements in unpredictable environment; development of 2-joint-arm robot that is driven by three pairs of antagonistic actuators.

## II. THE MECHANISM OF CONSTRAINTS EMERGENCE/SATISFACTION IN BIPEDAL WALKING

Bipedal locomotion is a movement of the body carried out by cyclical and dynamical interactions of the legs with the ground. During the bipedal locomotion in the real world, the body will receive unpredictable forces depending on various factors, e.g., changes of the ground-conditions, changes of the wind- conditions (such as a tail or head wind) and etc. Perturbations to the movement of the body caused by these forces depend on the condition of the system-itself, that is, dynamical properties of the body. For example, the posture of the body will be directly affected by the forces if the stiffness of the body is high and will not be affected if the stiffness is low. Because the biological system has an ability to change various dynamical properties of its own body, an appropriate control of those properties is important for the system to maintain the locomotion in the real world.

Muscle-tone is one of important parameters to determine the properties of the body, such as the stiffness and the viscosity. To adapt unpredictable changes of the environment, the muscle-tone should be appropriately set before the movement depending on an aim supposed by the system-itself, and should be controlled during the movement depending on

conditions of the environment. We constructed the model of bipedal walking system shown in Fig. 1. Simulation results indicated that flexible and robust bipedal locomotion can emerge from appropriate control of the muscle-tone depending on the ground reaction force (Fig. 2). Furthermore, it was found that the proposed model is useful for theoretically analyzing various kinds of motor ataxia.

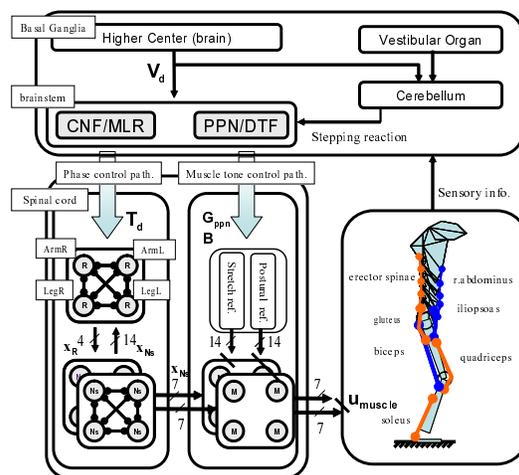


Fig. 1. Bipedal walking model.

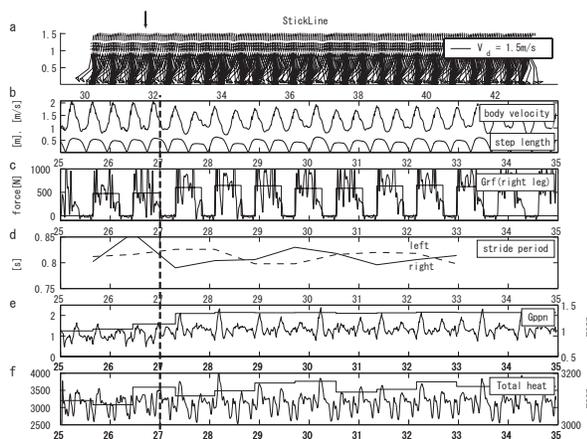


Fig. 2. Simulation result. 20kg weight is added to the waist during a walk.

## III. MODELING THE CONTROL MECHANISMS FOR REACHING MOVEMENTS

Fig.3 shows an impedance map of the body. Elements in top and bottom rows correspond to dimensions of 'motion'

and ‘force’, respectively, and three columns represent configuration spaces of the body (left, hand-space; middle, joint-space; right, muscle-space). To transform one dimension to the other or one space to the other, respective matrices are needed. The computational task for the reaching movement control is to calculate commands for the muscle force from the information about the hand position. For this task, some of the matrices have to be determined. However, this problem is ill-posed because the biological system is redundant. To determine the necessary matrices, there must be a constraint. For the reaching movement in the real world, the constraint itself should be adaptable to the unpredictable changes. In the followings, we propose two mechanisms, in which constraints emerge in real time from interactions between the system and environment during the movement.

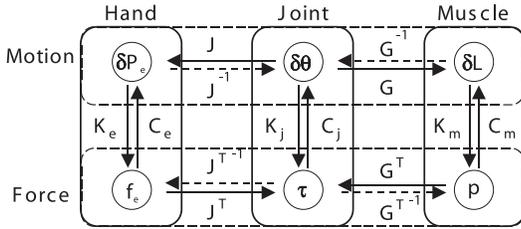


Fig. 3. An impedance map of the body for reaching movement.

#### A. THE AUTONOMOUS DECENTRALIZED ARM REACHING MODEL USING KINEMATICALLY COMPUTED ‘MOBILITY MEASURE’

For controlling planar  $m$  joints arm (Fig. 4), our autonomous decentralized model was implemented as follows. First, a real-time hand command, termed as a desired hand velocity,  $\mathbf{v}_d$ , is calculated as:

$$\mathbf{v}_d = G_t(\mathbf{x}_d - \mathbf{x}), \quad (1)$$

where,  $\mathbf{x}_d$ ,  $G_t$ ,  $\mathbf{x}$  are a desired hand position, a gain factor, and a current hand position, respectively. Second, a command for a joint  $i$ ,  $\tilde{\mathbf{v}}_{di}$ , is determined by a following autonomous decentralized network:

$$\tilde{\mathbf{v}}_{di} = \prod_{j \neq i}^m (1 - k_j) \mathbf{v}_{di}^l + \sum_{j \neq i}^m k_j \mathbf{v}_{dj}^{cj}, \quad (2)$$

where,  $\mathbf{v}_{di}^l$  is a component of  $\mathbf{v}_d$  that the joint  $i$  can generate by its own rotation (we termed as a local vector, Fig.4 A), and  $\mathbf{v}_{dj}^{cj}$  is a residual component of  $\mathbf{v}_d$ , which a joint  $j$  requests the joint  $i$  to generate (we termed as a coupling vector, Fig.4 B).  $k_i$  is a ‘‘mobility measure’’ calculated from sensory information representing how the joint  $i$  is currently mobile. The mobility measure is defined as:

$$k_i = \exp[-4 \ln 2 ( \|\mathbf{v}_{di}^l - \mathbf{v}_i\|^2 + 1 ) / ( \|\mathbf{v}_{di}^l\|^2 + 2 ) ], \quad (3)$$

where,  $\mathbf{v}_i$  is a velocity resulted by a rotation of the joint  $i$ . 1 and 2 are tiny terms. When the joint  $i$  is mobile/immobile, it approaches to 1/0. Finally, using a simple inverse kinematics and a velocity feedback, a desired angular speed,  $\dot{\theta}_{di}$ , and a desired joint torque,  $\tau_{di}$ , for the joint  $i$  are calculated as:

$$\dot{\theta}_{di} = \tilde{\mathbf{v}}_{di} \cdot \mathbf{e}_{xi} / \|\mathbf{a}_i\|, \quad (4)$$

$$\tau_{di} = G_i(\dot{\theta}_{di} - \dot{\theta}_i). \quad (5)$$

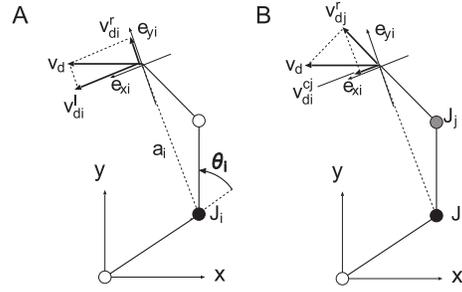


Fig. 4. Three-joint arm model. A: Definition of local vector for joint  $i$  and its residual vector. B: Definition of coupling term relating joint  $j$  and joint  $i$ .

where,  $G_i$  is a feedback gain factor. As a result, Eq. (5) represents the controller for each joint in autonomous decentralized form.

Simulation results indicated that the mobility measure,  $k_i$ , appropriately evaluates the changes of the kinematical and/or mobility caused by unpredictable change of body and/or environment, and the controller can autonomously shift the dominant joint depending on the movement directions and the target shift during the movement, or can carry out the movement from the fully-stretched, singular configuration.

The autonomous decentralized form of Eqs. (4) and (5) can be transformed into combined matrix forms as follows:

$$\dot{\theta}_d = \left[ \mathbf{K}_l \mathbf{D}^{-1} \mathbf{J}^T + \mathbf{D}^{-1} \mathbf{J}_\perp^T \mathbf{J} \mathbf{D}^{-1} \mathbf{K}_c \mathbf{J}_\perp^T \right] \mathbf{v}_d, \quad (6)$$

$$\boldsymbol{\tau}_d = \tilde{\mathbf{J}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})^T G_t(\mathbf{x}_d - \mathbf{x}) - \mathbf{G}\dot{\boldsymbol{\theta}}. \quad (7)$$

$\tilde{\mathbf{J}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$  is defined as:

$$\begin{aligned} \tilde{\mathbf{J}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) & \\ & \equiv \left[ \mathbf{G} \mathbf{K}_l \mathbf{D}^{-1} \mathbf{J}^T + \mathbf{G} \mathbf{D}^{-1} \mathbf{J}_\perp^T \mathbf{J} \mathbf{D}^{-1} \mathbf{K}_c \mathbf{J}_\perp^T \right]^T. \end{aligned} \quad (8)$$

Eq. (8) varies depending on  $k_i$  in real-time, and it transforms the desired hand velocity into the joint torque. Thus, we call Eq. (8) as a variable Jacobian matrix. The variable Jacobian matrix plays an important role in adaptability of our controller as a whole system. This implies that our autonomous decentralized controller enables the system to create the transformation matrix with the adaptive function in real-time based on sensory information.

#### B. THE POSTURE CONTROLLER BASED ON THE DYNAMICAL INFORMATION

Force and torque that would affect a body posture can be divided into ‘‘active elements’’ (that are caused by muscle-outputs) and ‘‘passive elements’’ (that are caused by movements of body itself and external forces). We call the active elements as ‘‘muscle-torques’’ and the passive elements as ‘‘interaction-torques’’. The interaction torques include inertia force, counteracting force or torque, and Coriolis force. In the biological system, there are many kinds of mechanoreceptors in muscles and joints, which can detect forces applied to each part of the body. So, in our computational

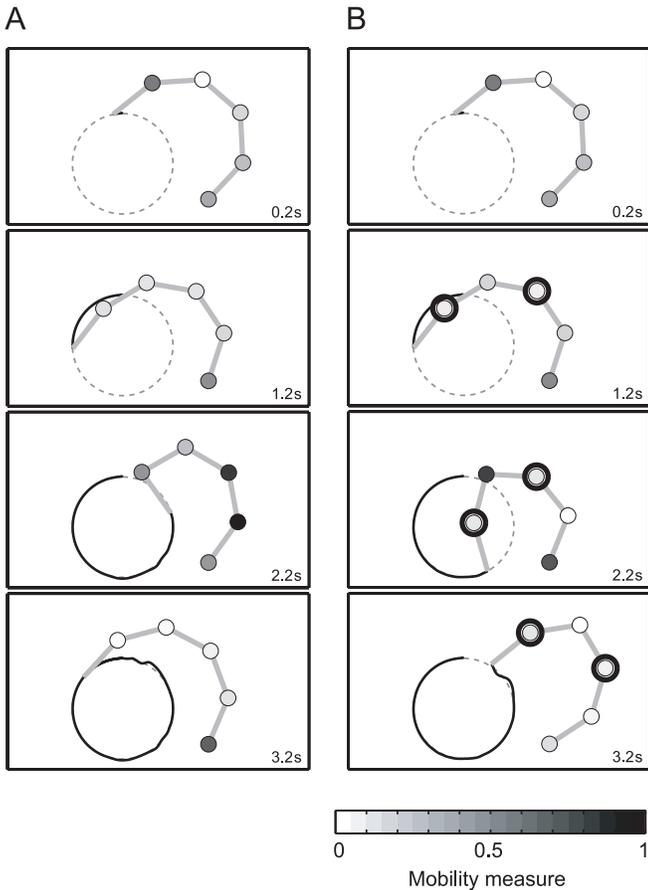


Fig. 5. Rotating movements by 5 dof arm. A: Normal condition. B: Perturbed condition, in which the viscosity of the two joints 3 and 5 were abruptly increased from 0.4 to 10 kg m<sup>2</sup>/s during motion (shown by tick circles). Joint color shows which joint is instantaneously mobile. Black: mobile joint ( $k_i = 1$ ). White: immobile joint ( $k_i = 0$ ).

model, it was assumed that the muscle-torques and the interaction-torques are distinctively detectable in real time.

The system could not control the interaction torques directly. However, the system can use the muscle torques to change its body posture, and consequent posture changes would affect interaction-torques applied to each link of the body. If the system can change postures of each link so that the interaction torques for link  $i$  would support the active muscle torques for link  $i$ , the body posture might become a posture, in which the system would use the active muscle torques effectively for carrying out movement purposes. So, a controller was designed to detect and compare the muscle- and interaction-torques, and then to generate commands for changing the posture of each link that makes the muscle torques to work effectively.

We implemented the controller into the 3-link-3-joint model in autonomous decentralized manner, and examined how the model changes its posture when an external force is applied to the hand-end. The simulation result is shown in Fig.6. In this case, the final posture of the model corresponded to a posture with the minimum sum of torque squares calculated analytically. This implies that, using control pathway of the “force” dimension (Fig. 3, bottom row),

the system can optimize its posture based on the dynamical information of the body.

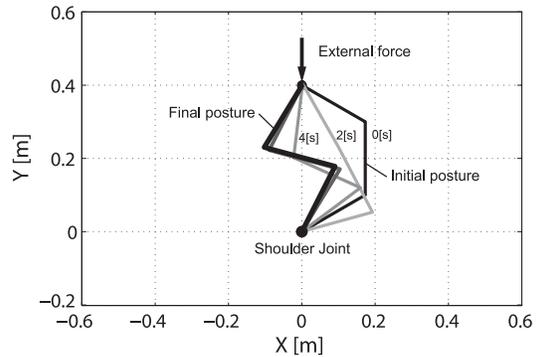


Fig. 6. Simulation result of the posture controller. External force (10N) was added to the hand. As a result, model was able to change own posture to the analytically optimal posture. The stick figure was traced every 1.0 second.

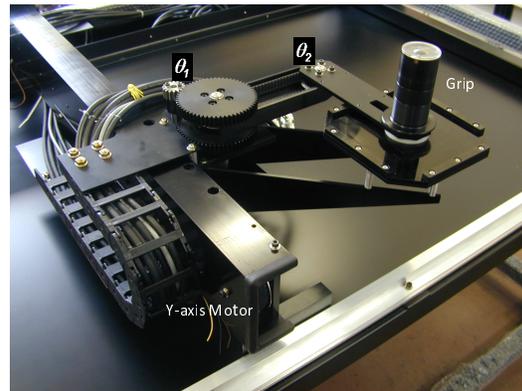


Fig. 7. Slider mechanism of the Manipulandum.

#### IV. ANALYSIS OF ARM REACHING MOVEMENTS IN UNPREDICTABLE ENVIRONMENT

To examine how we adapt ourselves to a newly environment in one trial, we developed a new manipulandum system that enable us to analyze human arm reaching movement under various visual and mechanical perturbations (Fig. 7). The manipulandum includes two independent mechanical servo systems, position and force one. When a subject moves the servo driven grip, frictional force that a subject feels is small (only few newtons) and subjects can move their hand naturally. The visual information of the hand-end is given by a projector controlled by the PC.

Using the manipulandum, we measured the arm reaching movements when visual information of the hand position was rotationally transformed at various degrees from the original hand position in trial-by-trial. Typical results are shown in Fig. 8. By moving the hand, subjects first got the information about the visual rotation angle, and then adjusted their hand movement to reach the goal in each trial. Repeated execution of the movements in unpredictable rotation angles made this

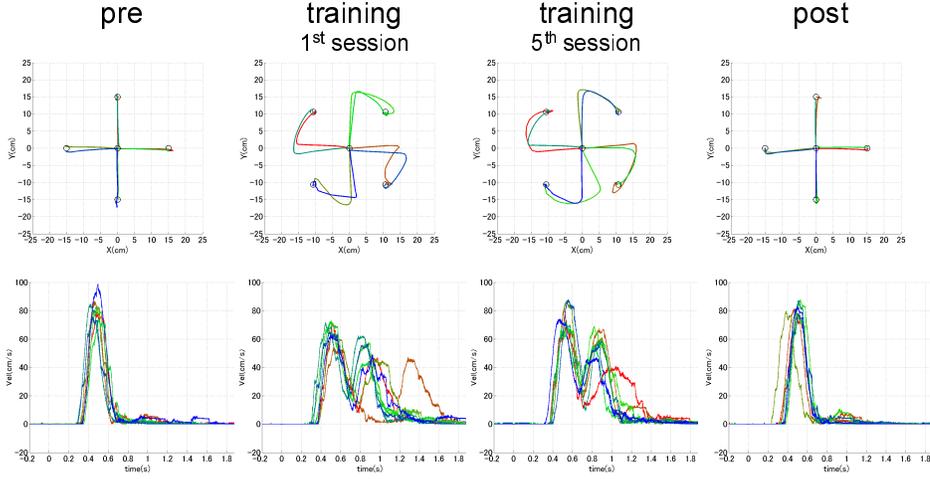


Fig. 8. Typical reaching movements during the visual rotation task. The visual rotation angle (VRA) is 0 degree in pre- and post-sessions, and one of 0,  $\pm 45$ ,  $\pm 90$ ,  $\pm 135$ , or 180 degree during training sessions. In this figure, panels of the training sessions only show the results when  $VRA = 45$  degree. Top, trajectory of the hand-end; Bottom, velocity profile of the hand-end.

adjusting process faster. We also found that the degree of unpredictability during the reaching task might affect the adjusting strategy.

### V. DEVELOPING THE ARM ROBOT

Redundancy of the body and actuator enables the biological system to generate various motion patterns. By using the sensory information, the biological system can generate appropriate motions according to environmental conditions. The controller that we have proposed is designed to take full advantage of such characteristics of the biological body for generating adaptive motions. To examine the performance of the proposed controller in the real world, we designed and developed a redundant arm robot that has redundant (agonist and antagonist) actuators and various kinematical and dynamical sensors (Fig. 9). In this redundant robot, joint impedance can be controlled by co-contracting the antagonistic muscles. This is a great advantage of the driving method, like human does. So, we evaluated whether the robot system can control joint impedance by using the antagonistic muscles. Fig.10 shows temporal changes of the shoulder angle when the co-contraction torque was set at one of three values and a fixed external force was applied to the shoulder as a perturbation. The converged joint angle depends on the amplitude of antagonistic torque, indicating that that the joint impedance can be controlled by co-contracting the antagonistic muscle in our system.

### VI. CONCLUSION

We clarified that the emergence and satisfaction of constraints based on the real time information about body and environment are essential for the control system of walking and arm reaching movements in unpredictably changing environment. The proposed control mechanisms can be a principle mechanism for systems working flexibly in the real world.

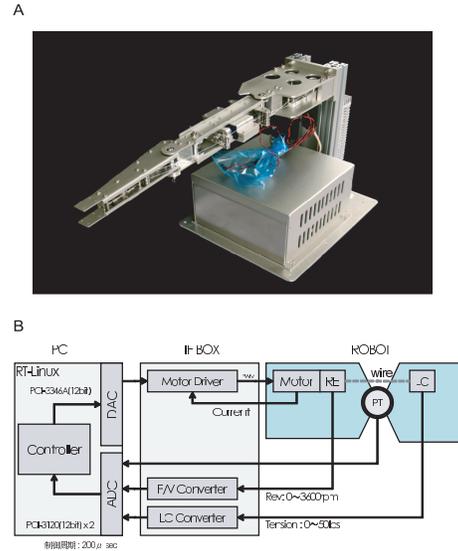


Fig. 9. The robot system with 2-joints-6-muscles. A: Overview. B: Block diagram of the control system.

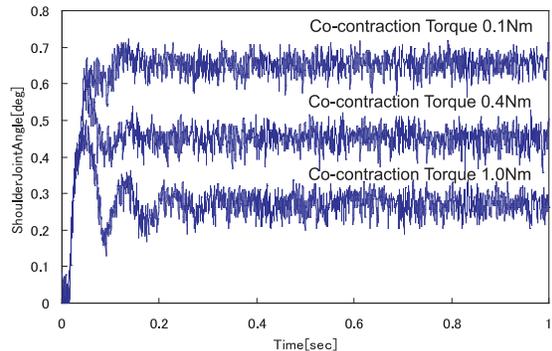


Fig. 10. Modulation of joint impedance due to co-contraction.

# D01-02: Discovery and Development of Dynamical Common Principle of Mobiligence

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## I. INTRODUCTION

The Group D searching a common principle of Mobiligence was intended to find a core principle of Mobiligence and devised a structure hypothesis of various movement intellect so far. As a result, we came to bring about a thought called Dual Structure of Mobiligence which consists with the Implicit Control and the Exprilcit Control as one hypothesis.

In this note, we show a special solution of the Mobiligence Problem as the first step. Doing so, we try to show the existence of a general solution of the Mobiligence Problem

Concretely, we introduce a simple but very important example. The example is a kind of configuration problem of manipulator and we can easily find Implicit Control Law.

## II. IMPLICIT CONTROL LAW

In this chapter, we define a problem of embedding to attack the problem of indivisibility, and propose a concept of Implicit Control Law as a solution for the problem[1].

### A. How to treat the overlapping

In control system of biological system, there are various pattern of Problem of Indivisibility. In this section, we consider a method for treating these patterns uniformly. The point of this is how to treat the overlapping.

After some considerations, we came to think that the following idea must be an effective method for solving the overlapping problem. The idea is to introduce an another element which is sandwiched between the Plant and the Control Law instead of overlapping. That is, as a solution to the Problem of Indivisibility, we propose the block diagram shown in right hand side of Fig.1 instead of the block diagram shown in left hand side of Fig.1.

### B. Problem of Embedding and Implicit Control Law

From the above discussions, we formulate the following problem.

**Def.2:Problem of Embedding** : Problem of embedding can be defined as the problem which makes clear the possibility that a kind of control law appears by interacting with plant and field. See the right hand side of Fig.1. And, "to answer the following questions" is defined as "to solve the problem". (i) Clarify whether such an element is embedded in the control system or not. (ii) If there is a possibility, then show us the element clearly. □

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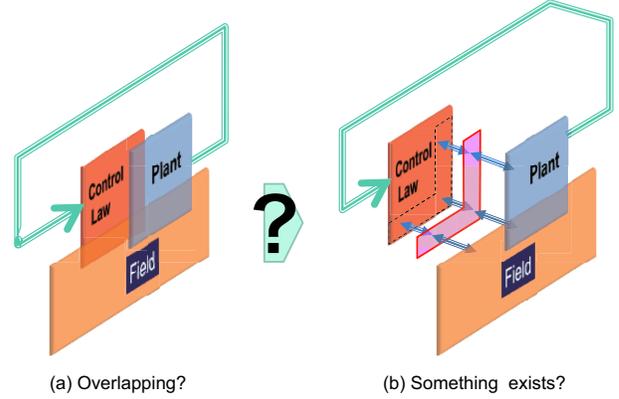


Fig. 1. Overlapping or something exists?

Furthermore , if some kind of control law can be found, then let's define the following partial implicit control laws.

**Def.3:Explicit Control and Implicit Control:** When a kind of element which appears by interaction between Plant $P$  and control law can be recognized as an another control law, then call this element as Implicit Control Law $C_I$ . The remainder element We call an element which remained after substract Implicit control law from control law as Explicit Control Law $C_X$ . See Fig.2 . Therefore, Control Law consists of Explicit Control Law and Implicit Control Law as shown in the next equation.

$$C = C_X \oplus C_I \quad (1)$$

Where,  $A \oplus B$  implies composition of  $A$  and  $B$  without common set. □

Furthermore, we divide the Implicit Control Law as the following.

**Def.4:Decomposition of Implicit Control:** Implicit Control Law consists with the three parts as shown in the next equation. See Fig.2 .

$$C_I = C_F \oplus C_P \oplus C_{FP} \quad (2)$$

Here,

- $C_F$  Field dependent Sub-Implicit Control Law,
- $C_P$  Plant dependent Sub-Implicit Control Law,
- $C_{FP}$  Plant and Field dependent Sub-Implicit Control Law.

□

When we observe decerebrate cat[2] and a slime mold, an amoeba, their behavior seemed to be able to be realized

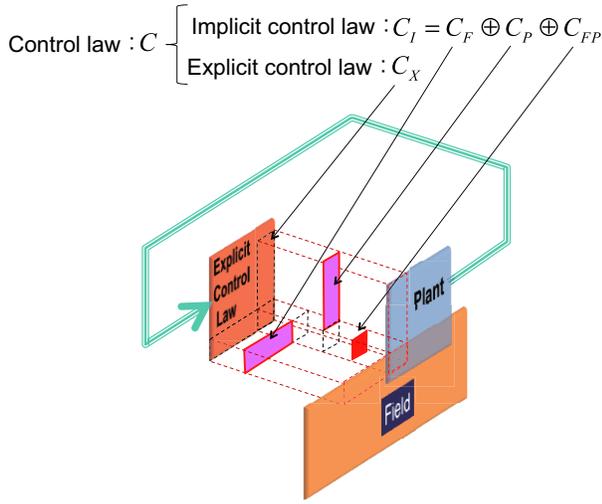


Fig. 2. Structure of implicit control law

(even if or an effect becomes small) without Explicit Control Law. In addition, if we see various results concerned with passive dynamic walking[3][4] [5] which can be regarded as a system without Explicit Control law, we can say the existence of Implicit Control Law.

### C. Special Solution of Implicit Control Law

From the above discussion, to consider the biological control, we gradually focus a target and we found that we should locate the Implicit Control Law as the first step. Therefore, we discuss the Implicit Control Law in this section.

We have not yet found the general formulation of Implicit Control Law, we can show you the Implicit Control Law in a special cases. That is to say, we can show you some special solutions. At this stage, we expect that, by showing some special solutions, we may show the existence of general solution including the special solutions. See Fig.3.

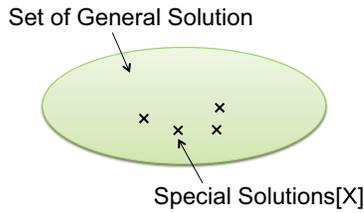


Fig. 3. General and Special solutions

One method for finding a special solution is to find and arrange a special situation in such a situation feedback loop and Explicit Control Law disappear. The conditions for the motion is the following.

**Def.5:Condition of Motion:** We call the motions which satisfy the following conditions as Open loop and decoupling motion.

- 1) The motion has a meaning.
- 2) The motion is stable. That is, the motion can be realized with no external input. □

In this section, considering a motion which satisfies the above conditions, we show an example of Implicit Control Law[1] .

Consider an attitude control problem of manipulator in the gravity field shown in the left hand side of Fig.4. The first joint is fixed on the ground. In this case, the Field is the gravity field. Here, for simplicity, suppose that the all joints are rotary type and the all axis of the joint are perpendicular to the paper. Each joint has no friction torque and can be supplied input torque.

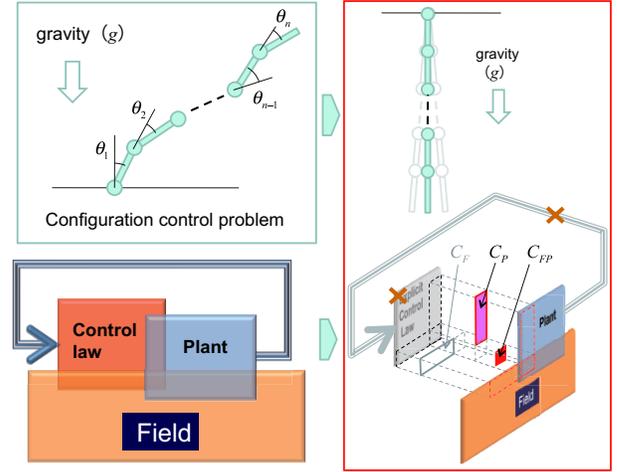


Fig. 4. From closed loop system to open loop system

Among the set of attitude control problems, we can find the next special problem which satisfy the above Condition of Motion. The problem is this. As shown in the right hand side of Fig.4, let us consider the problem of the attitude control problem: Let the manipulator straight to the downward.

Actually, this is a realistic attitude problem and we can easily check that this motion satisfies the above Condition of Motion. In the following, we confirm this intuition and show the Implicit Control Law in this case. That is to say, we solve the Problem of Embedding.

At first, the dynamical equation of the manipulator can be obtained as

$$J(\theta) \ddot{\theta} + c(\theta, \dot{\theta}) + B\dot{\theta} + h(\theta, g) = u. \quad (3)$$

Where,  $\theta = [\theta_1, \theta_2, \dots, \theta_n]^T$  is a joint angle vector and set  $\dot{\theta} = 0$  when the manipulator straight downward. The  $u$  is  $n$  dimensional input torque vector, the  $J(\theta)$  is a inertia matrix, the  $c(\theta, \dot{\theta})$  is a centrifugal and Corioli's torque, the  $B\dot{\theta}$  is the viscosity friction torque term. The  $B = \text{diag}[B_1, B_2, \dots, B_n]$  is the coefficient of viscosity friction of each joint. The  $h(\theta, g)$  is the acceleration of gravity, and  $h(\theta, 0) = h(0, g) = h(0, 0) = 0$ .

Here, we have the following result.

**Result 1:** In case of the attitude control problem of manipulator, the sub-implicit control laws  $C_P$  and  $C_{FP}$  can

be obtained as the following.

$$C_P : u_P = -B \dot{\theta} \quad (4)$$

$$C_{FP} : u_{FP} = -h(\theta, g) \quad (5)$$

See Fig.5. □

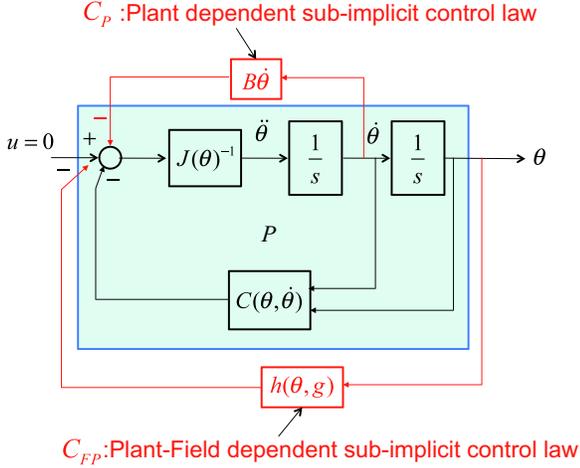


Fig. 5. Two implicit control law in manipulator configuration control problem

**Proof** In Eq.(3)(manipulator), if we set a target attitude as  $d = [0, 0, \dots, 0]^T = 0$ , then we have  $\lim_{t \rightarrow \infty} \theta(t) = d$  with  $u = 0$ . From the proof of this fact ( for example see[6]), we can see that the term  $u_P$  produces the asymptotic stability of the state, and the term  $u_{FP}$  control the attitude of the manipulator to the target attitude. And in this case, because  $u = 0$ , then we have no Explicit Control Law. So, we have no  $C_F$ . Furthermore, the term  $u_P = -B \dot{\theta}$  is not field dependent term, but is plant dependent term. And the term  $u_{FP} = -h(\theta, g)$  is field dependent term. Concretely, by change of the acceleration of gravity, this term also changes. Also, this term change by the change of the physical parameters of the manipulator. That is to say, the term  $u_{FP}$  is the field and plant dependent term.

From these discussion and the definition of  $C_P$  and  $C_{FP}$ , Eq.(4) can be regarded as the Plant dependent Sub-Implicit Control Law and Eq.(5) can be regarded as the Field and Plant dependent Sub-Implicit Control Law.

Here, we have to notice that these implicit control laws work on the specified target. That is to say, if the task changes, then the suitable implicit control law also should change. □

In the previous example, we show the two of three Sub-Implicit Control Laws ( $C_P$  and  $C_{FP}$ ). We have not introduce the third one:  $C_F$ . It is assumed that this Sub-Implicit Control Law  $C_F$  is born between Explicit Control Law  $C_X$  and Field  $F$ . Therefore, to have  $C_F$  in the individual, the individual system has to have a kind of high level Explicit Control Law.

That is, we can say that such a system must have a high level adaptive motor function. In addition, the interaction between Field and Explicit Control Law may not be done by

dynamical effect but be done by information effect. We have not yet been carrying out precise discussion on this point. But we are thinking that this topics must be related with the idea of Emergence of Constraints proposed by Yano[7].

### III. IMPLICIT CONTROL LAW AND REALTIME ENVIRONMENTAL ADAPTATION FUNCTION

Above, we introduced the Implicit Control Law as one solution for the Problem of Indivisible in the creature control system. Moreover, this Implicit Control Law can be understood as an important key for the expression of the realtime environment adaptation function that a creature had.

In this chapter, we investigate  $C_{FP}$ , which seem to have the strongest relationship to the environment adaptive function, from an adaptive functional point of view. The result shown in the previous section was restricted very simple one ( special solution: see Fig.3). But, the result implies the possibility of existence of general solution of Implicit Control law.

As see the following, the  $C_{FP}$  is the most important for appearance of realtime adaptive motor function of biological systems. Till now, we expressed that the Sub-Implicit Control Law  $C_{FP}$  is appeared by interaction between plant and field. Actually, in case of the attitude problem of manipulator, the Sub-Implicit Control Law  $C_{FP}$  appears when the manipulator is in the gravity field, and disappears when the gravity field is removed ( that is  $g = 0$ ).

Thus, the following "summary" is obtained. See Fig.6.

The Sub-Implicit Control Law  $C_{FP}$  is the implicit control law which is appeared by the interaction of field  $F$  and plant  $P$ . And, this is induced by the feedback structure constructed between plant and field. We call this feedback structure "Implicit Feedback structure". The Sub-Implicit Control Law  $C_{FP}$  disappear with disappearing the interaction of field  $F$  and plant  $P$ . The SUB-Implicit Control Law  $C_{FP}$  changes in realtime according to realtime variation of the field  $F$ .

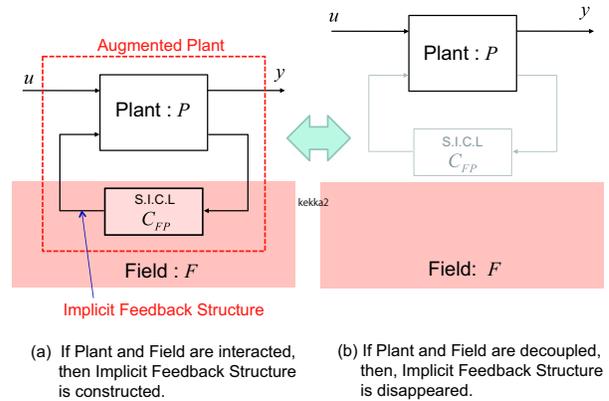


Fig. 6. Appearance and disappearance of  $C_{FP}$

Integrating the above considerations, we can have the following our understanding of the realtime adaptive motor function of living things.

The field surrounding the living things changes in various factors. The change will occur by the change of the field itself. The field seen from the living thing changes by the movement of the living thing. To cope with these changes, living things seem to embed a kind of adaptive function so as to maintain the internal state or itself optimal. If they do not do so, their life become danger.

Then, we can naturally derive an assumption that the element which can have such an adaptive function may be the Explicit Control Law  $C_X$ . Because the Implicit Control Law is constrained by the Field or the Plant, the element is not suited for the element.

From these discussion we have the conclusion of this paper.

**Conclusion: Realtime Environmental Adaptation Function:** We understand the realtime environmental adaptation function of the living thing as the following.

- C1 [Existence] The realtime environmental adaptation function of the living thing come from the Sub-Implicit Control Law  $C_{FP}$ .
- C2 [Function] The function of the realtime adaptation of the living thing is a function which adjusts the Explicit Control Law  $C_X$  so as to utilize the characteristics of Implicit Control Law  $C_{FP}$  efficiency. See Fig.7.
- C3 [Understanding] To understand the realtime adaptive ability of the living things, we have to know both Explicit Control Law  $C_X$  and Implicit Control Law  $C_I$  simultaneously. Especially, because the Implicit Control Law never exists outside the Field, if you take the living thing out of the field and put it in your laboratory, you never understand the realtime adaptive ability. Of course, in this case, you can understand the ability of the Explicit Control Law  $C_X$ . But this does not mean that you can understand the whole ability which we want to know. □

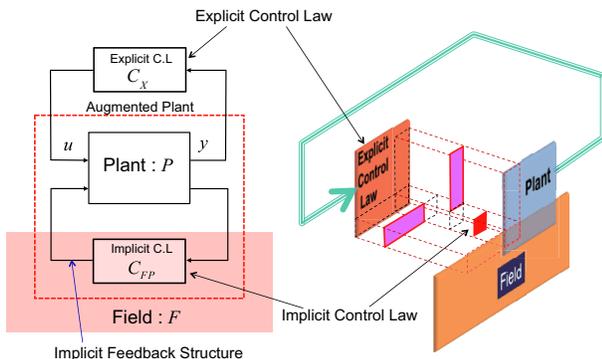


Fig. 7. Explicit Control Law and Implicit Control Law

#### IV. CONCLUSION

In this paper, we proposed a concept of Implicit Control Law. And we led that both understanding of the Explicit Control Law and the Implicit Control Law are necessary to

understand the realtime environmental adaptation function of the living things ( Mobiligence). From this point of view, we can say that the traditional researches concerned with this topics have been concentrated to only the research of the Explicit Control Law.

From now on, introducing the Implicit Control Law, we have to carry out re-thinking of the realtime environmental adaptive function.

If we see some moving things, we often wonder why they can behave in such a complicated manner with very simple control law. This feeling can be obtained from not only living things but also artificial things. Especially, we strongly feel the feeling when we see the behavior of insects who has only tiny brain. The typical example is the anthill[8][9]. At this stage, we are convinced that this anthill have never built by only Explicit Control Law of the ants. The Implicit Control Law must be constructed by interaction with the Field.

Finally, we can say that, at this stage, we understand the problem of Mobiligence. This means that we understand the location of the problem of Mobiligence and clarified the essence of the problem. That is to say, what we have to do from now is to focus our consciousness to the Implicit Control Law.

#### REFERENCES

- [1] K.Osuka, A.Ishiguro and X.Zheng : On Implicit Feedback Structure embedded in Control System , Proc. 38th SICE Symposium on Control Theory, pp.271-276 (2009) (in japanese)
- [2] T. G. Brown : Decerebrate Cat Movie (1939), in Video: The Basal Ganglia and Brainstem Locomotor Control, by E. Garcia-Rill (1989)
- [3] K.Osuka and K.kirihara : Motion Analysis and Experiment of Passive Walking Robot Quartet II , J. of the Robotics Society of Japan , Vol.18-, No.5, pp.737-742 (1999) (in Japanese)
- [4] Y.Sugimoto and K.Osuka : Stability Analysis of Passive Dynamic Walking – An Approach via Interpretation of Poincare Map’s Structure , Transactions of Institute of Systems, Control and Information Engineers, Vol.18, No.7, pp.255-260 (2005) (in Japanese)
- [5] D.Owaki, K.Osuka and A.Ishiguro : Understanding of the Stabilization Mechanism underlying Passive Dynamic Running , The 26th Annual Conf. of the Robotics Society of japan, 3B1-09 (2008) (in Japanese)
- [6] S.Arimoto : Dynamics and Control of Robot , Asakura Publishing Co., Ltd. (2002) (in Japanese)
- [7] M.Yano, N.Tomita and Y.Makino : Emergence of Constraints for Voluntary Movement , J. of the Society of Instrument and Control Engineers, Vol.44, No.9, pp.590-595 (2005) (in Japanese)
- [8] <http://australianpelican.blog54.fc2.com/blog-entry-520.html> (in Japanese)
- [9] Mike Hansell: Built by Animals: The natural history of animal architecture ( Trans. by K.Nagano and M.Akamatsu), SEIDOSYA Inc. (2009) (in japanese)

# A Collective Behavioral Approach with Coupled Oscillators to Understanding Mobiligence

Akio Ishiguro, Masahiro Shimizu, and Kazutoshi Gohara

**Abstract**—This paper discusses experimental verifications of a two-dimensional modular robot called “Slimebot”, consisting of many identical modules, each of which has simple motile functions. We have so far investigated a fully decentralized algorithm able to control the morphology of the modular robot in real-time according to the environment encountered. One of the most significant features of our approach is that we explicitly exploit “emergent phenomena” stemming from the interplay between control and mechanical systems. In order to verify our proposed control scheme, we have constructed real physical Slimebot. Experiments with 10 modules suggest that this robot exhibits significant abilities, i.e., adaptivity and scalability.

## I. INTRODUCTION

The behavior of a robot emerges through the dynamics stemming from the interaction between the control system, mechanical system, and environment[1]. Considering the fact that the control and mechanical systems, which are usually the targets to be designed, are positioned at the source of this interaction, they should be treated with equal emphasis in the design process. However, as can be seen from the terms of “control system and controlled system” or “controller and controlled object”, traditionally these two systems have been clearly distinguished according to their dominant relationship. More specifically, system enhancement has been achieved mainly by increasing the complexity of its control system. This, however, causes serious problems, particularly in terms of adaptability and energy efficiency.

Under these circumstances, recently the importance of the following suggestions has been widely recognized:(1) there should be a “well-balanced coupling” between control and mechanical systems; and (2) under which one can expect that quite interesting phenomena, e.g., realtime adaptability and high energy efficiency, will emerge. However, there still leaves much to be understood about how control and mechanical systems, i.e., brain and body, should be coupled.

Based on the above consideration, we have so far developed a two-dimensional modular robot, called *Slimebot*(see Fig. 1). In this study, we have particularly focused on true slime mold (*Physarum polycephalum*, etc.)[2][3] since it exhibits significantly supple locomotion only with a purely decentralized control mechanism. That adaptive function



Fig. 1. A real physical Slimebot consisting of 10 modules.

(i.e., amoeboid locomotion) could be modeled by exploiting a modular robot[4]-[11] that is capable of changing shape and locomotion by altering the relative positional relationship between mechanical modules according to environmental changes. In order to realize an emergent adaptive control, the coupling between the control and mechanical systems of Slimebot has been carefully designed as follows: we have particularly focused on a *functional material*, i.e., a genderless *Velcro strap*, and *mutual entrainment* among nonlinear oscillators, i.e., *van der Pol(VDP)* oscillators, the former of which is used as a spontaneous connectivity control mechanism between the modules, and the latter of which acts as the core control mechanism for the generation of locomotion and ensures the scalability. The behaviors of the Slimebot are based on the same principle as well as the amoeboid locomotion generated by slime molds[2][3]. Simulation results indicate that the proposed method can induce amoebic locomotion, which allows us to successfully control the morphology of the modular robot in real time according to the situation without losing the coherence of the entire system. To verify the feasibility of our proposed method, experiments with a real physical Slimebot are also significantly important in order to verify the validity of the proposed method with a high degree of reliability.

This paper is organized as follows: In the section 2, the design strategies of the Slimebot are explained; The experimental results are presented in the section 3; And, the paper is finalized with conclusions and the future works.

## II. DESIGN STRATEGIES

So far, we have confirmed real-time adaptive reconfiguration under the simulations (see Fig. 2)[12]. In what follows, the design strategies introduced in this study are explained.

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### A. The Mechanical Structure

A two-dimensional Slimebot has been developed, consisting of many identical modules, each of which has a mechanical structure like the one shown in Fig. 3 and 4. Each module is equipped with telescopic arms, a ground friction control mechanism, and an omnidirectional light-detecting sensor. Note that the module is covered with a functional material. More specifically, we used a genderless Velcro strap as a practical example, since this intrinsically has interesting properties: when two halves of Velcro contact each other, they are connected easily; and when a force greater than the yield strength is applied, the halves will come apart automatically. Exploiting the property of this material itself as a spontaneous connectivity control mechanism, we can expect not only to reduce the computational cost required for the connection control dramatically, but also to induce emergent properties in morphology control. The property of the connectivity control mechanism is mainly specified by the yield stress of Velcro employed: connection between the modules is established spontaneously where the arms of each module make contact; disconnection occurs if the disconnection stress exceeds the Velcro’s yield stress. We also assume that local communication between the connected modules is possible (see Fig. 4), which will be used to create phase gradient inside the modular robot (discussed below). In this study, each module is moved by the telescopic actions of the arms and by ground friction. Note that each module itself does not have any mobility but can move only by the collaboration with other modules.

### B. The Control Algorithm

Under the above mechanical structure, now we consider how we can generate stable and continuous locomotion. To

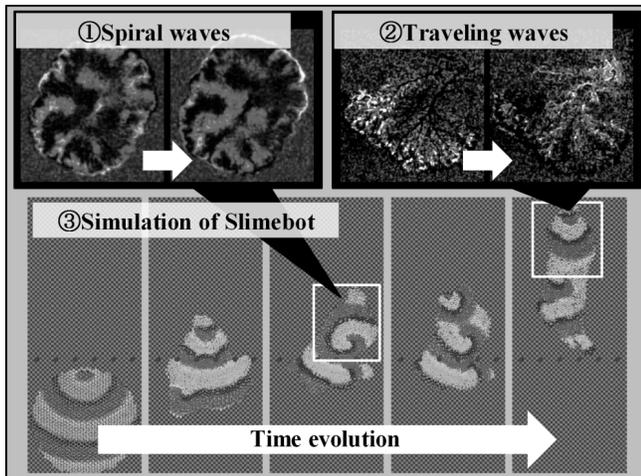


Fig. 2. Representative data of qualitative agreements between the Slimebot and rhythmic protoplasmic movement in the true slime mold. Note that no active control mechanism that precisely specifies connection/disconnection among the modules is implemented. Instead, a spontaneous connectivity control mechanism exploiting a functional material, *i.e.*, genderless Velcro strap, is employed. Experimental results (*i.e.*, a1 and a2) of true slime mold were provided by Prof. Takamatsu, Waseda University.

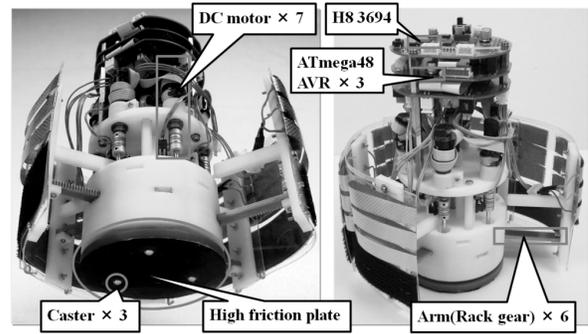


Fig. 3. Photo of the real physical module. The module has 7 DC motors, 6 motors of which are for extension/contraction of the arms, and the rest is for the ground friction control mechanism.

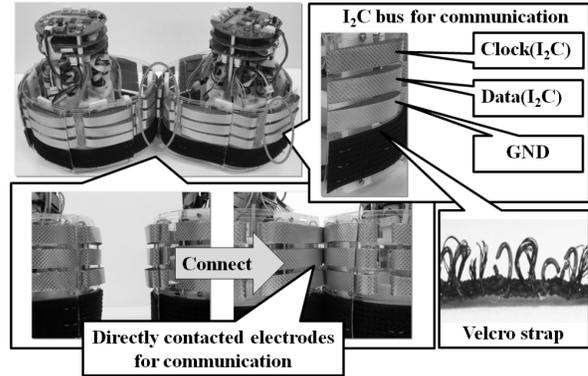


Fig. 4. The physical connection control mechanism by exploiting genderless velcro straps.

this end, a nonlinear oscillator is implemented onto each module, allowing us to generate rhythmic and coherent locomotion through the *mutual entrainment* among the oscillators. In the following, we will give a detailed explanation of this algorithm.

**Active Mode and Passive Mode:** Each module in the Slimebot can take one of two exclusive modes at any time: *active mode* and *passive mode*. A module in the active mode actively contracts/extends the connected arms, and simultaneously reduces the ground friction. In contrast, a module in the passive mode increases the ground friction, and returns its arms to their original length. Note that a module in the passive mode does not move itself but serves as a *supporting point* for efficient movement of the module group in the active mode.

**Creating the Phase Gradient through Mutual Entrainment:** In order to generate rhythmic and coherent locomotion, the mode alternation in each module should be controlled appropriately. Of course, this control should be done in a *decentralized* manner, and its algorithm should not depend on the number of the modules and the morphology of the Slimebot. To do so, we have focused on the *phase gradient* created through the mutual entrainment among locally-interacting nonlinear oscillators in the Slimebot, exploiting this as a key information for the mode alternation. Therefore, the configuration of the resulting phase gradient is extremely

important. In the following, we will explain this in more detail.

As a model of a nonlinear oscillator, the *van der Pol oscillator* (hereinafter VDP oscillator) was employed, since this oscillator model has been well-analyzed and widely used for its significant entrainment property. The equation of VDP oscillator implemented on module  $i$  is given by

$$\alpha_i \ddot{x}_i - \beta_i (1 - x_i^2) \dot{x}_i + x_i = 0, \quad (1)$$

where the parameter  $\alpha_i$  specifies the frequency of the oscillation.  $\beta_i$  corresponds to the convergence rate to the limit cycle.

The local communication among the physically connected modules is done by the local interaction among the VDP oscillators of these modules, which is expressed as:

$$x_i = x_i^{\text{tmp}} + \varepsilon \left\{ \frac{1}{N_i(t)} \sum_{j=1}^{N_i(t)} x_j^{\text{tmp}} - x_i^{\text{tmp}} \right\}, \quad (2)$$

where  $x_i^{\text{tmp}}$  and  $N_i(t)$  represent the state before the local interaction, and the number of modules neighboring module  $i$  at time  $t$ , respectively. The parameter  $\varepsilon$  specifies the strength of the interaction. Note that this local interaction acts like a *diffusion*.

When VDP oscillators interact according to Equation (2), significant phase distribution can be created effectively by varying the value of  $\alpha_i$  in Equation (1) for some of the oscillators. In order to create an equiphase surface effective for generating locomotion, we set the value of  $\alpha_i$  as:

$$\alpha_i = \begin{cases} 0.7 & \text{if the goal light(attractant) is detected} \\ 1.3 & \text{if the module is outer surface} \\ 1.0 & \text{otherwise} \end{cases} \quad (3)$$

Note that except the modules detecting the attractant, the modules on the boundary, *i.e.*, the outer surface, have the value of  $\alpha_i = 1.3$ . This allows us to introduce a kind of effect of *surface tension*, which is indispensable to maintain the coherence of the entire system.

**Generating Locomotion:** Here, we consider a control algorithm exploiting the phase distribution created from the aforementioned mutual entrainment among the VDP oscillators. To do so, the two possible modes, *i.e.*, the active and passive modes, of each module should be appropriately altered according to the phase distribution that emerges. The timings of the mode alternation are propagated from the front to the rear inside the modular robot as traveling waves. In this study, the extension/contraction of each arm of module  $i$  in the active mode is determined according to the phase difference with its corresponding neighboring module. Due to this, the degree of arm extension/contraction of each module will become most significant along the phase gradient, enabling the entire system to move toward the attractant while maintaining its coherency.

### III. EXPERIMENTAL VERIFICATIONS

#### Connection and Disconnection between Real Physical

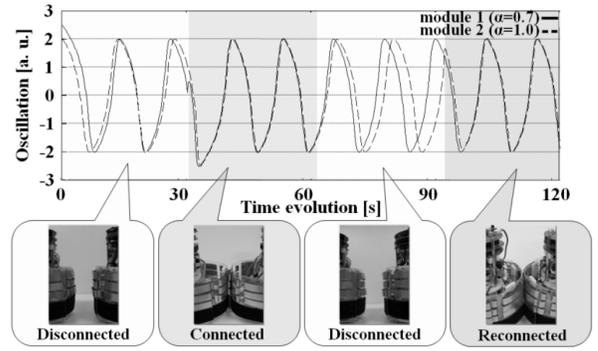


Fig. 5. A verification of connection mechanism.

**Modules:** We have verified the mechanism for mutual entrainment with two modules. As Fig. 5 shows, the oscillators of these modules can successfully exhibit mutual entrainment.

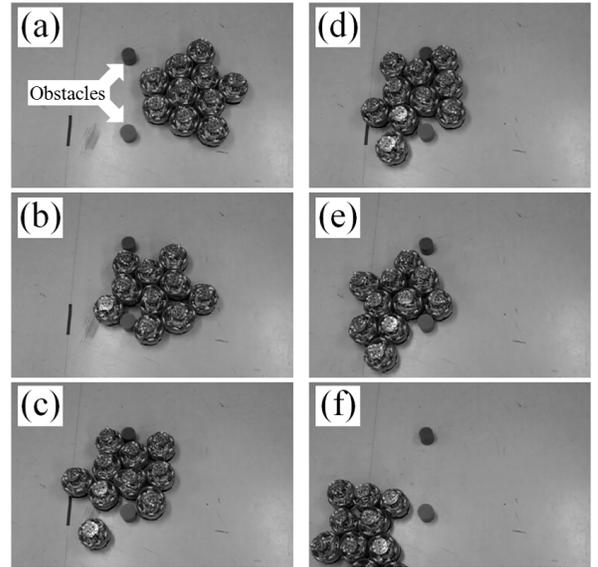


Fig. 6. Experimental verification of the adaptivity with 10 modules in the environment containing two cylindrical obstacles. See from (a) to (f).

**Experimental Verification of The Adaptivity:** Based on the above preliminary experiments, we verified the adaptivity. Fig. 6 shows the experimental result obtained. Time evolution developed in alphabetical order of snapshots. This figure explains the significant interesting result as follows: (a) first, the slimebot consisting of 10 modules started to locomote at an arrow-like configuration in the environment containing two cylindrical obstacles; (b) here, the Slimebot got stack around the obstacles at the moment; (c) then, the Slimebot got over the obstacle by disconnection between some modules; however, a module in frontal part ejected from the swarm after passing through the narrow aisle at this moment; (d) in this figure, interestingly, the ejected module at snapshot (c) gathered with the swarm; note that this is not only the effect of the functional material (*i.e.*,

velcro strap) but also mutual entrainment stemming from the coupled oscillators; (e) after that, the Slimebot passed through the obstacles by narrowing the width of the entire system; (f) finally, the Slimebot successfully negotiated its environment by the real-time adaptive reconfiguration. Note again that these behavior are not pre-programmed, but are totally emergent through the interplay between the control system (*i.e.*, coupled oscillators), the mechanical system (*i.e.*, velcro strap) and the environment (*i.e.*, two cylindrical obstacles).

**Experimental Verification of The Scalability:** Here, experimental verification of the scalability is shown. Fig. 7 indicates the result obtained. See from (a) to (d) in this figure. In contrast to the Fig. 6, (a) Slimebot here initially divided into 3 and 7 modules; (b) these modules are connected physically. (c)(d) the coherent swarm consisting of 10 modules locomote. Note that Slimebot consisting of various number of modules successfully perform amoeboid locomotion without any change of the control algorithm and parameters.

#### IV. CONCLUSIONS

In this study, we have developed a real physical modular robot that enables to control its morphology in real time by explicitly exploiting emergent phenomena stemming from the interplay between the control and mechanical systems. To this end, we have implemented a functional material (*i.e.*, genderless Velcro strap) and a locally-interacting nonlinear oscillator (*i.e.*, VDP oscillators) into each module, the former of which was utilized as a spontaneous connectivity control mechanism and the latter of which as a core mechanism for generating locomotion.

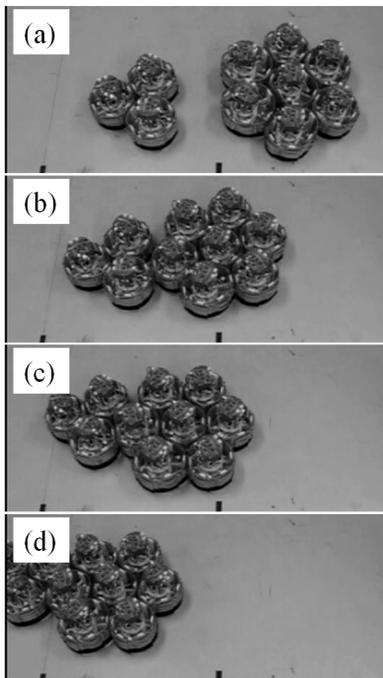


Fig. 7. Experimental verification of the scalability. See from (a) to (d).

The Slimebot successfully negotiated its environment (*i.e.*, obstacles) by the real-time adaptive reconfiguration. Note again that these behavior are not pre-programmed, but are totally emergent through the interplay between the control system (*i.e.*, coupled oscillators), the mechanical system (*i.e.*, velcro strap) and the environment (*i.e.*, two cylindrical obstacles). The experiments conducted suggest that our modular robot Slimebot is highly promising, which can be summarized as: (1) while each module is simply controlled with the VDP oscillator, adaptive reconfiguration can be self-organized according to the situation encountered; and (2) the spontaneous connectivity control mechanism provided by the functional material was fully exploited.

#### ACKNOWLEDGMENTS

This work has been partially supported by a Grant-in-Aid for Scientific Research on Priority Areas “Emergence of Adaptive Motor Function through Interaction between Body, Brain and Environment” from the Japanese Ministry of Education, Culture, Sports, Science and Technology. The authors would like to thank Prof. Atsuko Takamatsu, Waseda University, for frequent, stimulating, and helpful suggestions. Many helpful suggestions for the hardware of Slimebot from Ryo Matsuzawa, Takuma Kato, Hajime Takeda, Shintaro Yawata at our laboratory are greatly appreciated.

#### REFERENCES

- [1] H. Asama, et al., “System Principle on Emergence of Mobiligence and Its Engineering Realization”, in *Proc. of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2003, pp.1715–1720.
- [2] H. Miura and M. Yano, “A Model of Organization of Size Invariant Positional Information in Taxis of *Physarum Plasmodium* - A Reaction-Diffusion System Regulated by Phase of Chemical Oscillation -”, *Progress of Theoretical Physics*, Vol. 100, 1998, pp.235–251.
- [3] A. Takamatsu, et al., “Spatiotemporal Symmetry in Rings of Coupled Biological Oscillators of *Physarum Plasmodial* Slime Mold”, *Phys. Rev. Lett.*, Vol. 87, No. 7, 2001, pp.0781021–4.
- [4] T. Fukuda and Y. Kawauchi, “Cellular Robotic System (CEBOT) as One of the Realization of Self-Organizing Intelligent Universal Manipulators”, in *Proc. of IEEE ICRA*, 1990, pp.662–667.
- [5] S. Murata, H. Kurokawa, and S. Kokaji, “Self-Assembling Machine”, in *Proc. of IEEE ICRA*, 1994, pp.441–448.
- [6] A. Kamimura, S. Murata, E. Yoshida, H. Kurokawa, K. Tomita, and S. Kokaji, “Self-Reconfigurable Modular Robot – Experiments on Reconfiguration and Locomotion –”, in *Proc. of 2001 IEEE/RSJ IROS*, 2001, pp.590–597.
- [7] M. Dorigo, et al., “Evolving Self-Organizing Behaviors for a Swarm-bot”, *Autonomous Robots*, 2004, pp.223–245.
- [8] M. W. Jorgensen, E. H. Ostergaard and H. H. Lund, “Modular ATRON: Modules for a Self-Reconfigurable Robot”, in *Proc. of 2004 IEEE/RSJ IROS*, 2004, pp.2068–2073.
- [9] M. Yim, C. Eldershaw, Y. Zhang, and D. Duff, “Self-reconfigurable Robot Systems: PolyBot”, *Journal of the Robotics Society of Japan*, Vol.21, No.8, 2003, pp.851–854.
- [10] M. Asadpour, et al., “Graph Signature for Self-Reconfiguration Planning”, in *Proc. of 2008 IEEE/RSJ IROS*, 2008, pp.863–869.
- [11] S. Miyashita, et al., “Peltier-Based Freeze-Thaw Connector for Waterborne Self-Assembly Systems”, in *Proc. of 2008 IEEE/RSJ IROS*, 2008, pp.1325–1330.
- [12] A. Ishiguro, M. Shimizu, and T. Kawakatsu, “Don’t Try to Control Everything!/: An Emergent Morphology Control of a Modular Robot”, in *Proc. of 2004 IEEE/RSJ IROS*, 2004, pp.981–985.

# Studying Artificial and Biological Autonomy

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**Abstract:** This project is an experiment-oriented research study based on our theoretical ideas of autonomous systems. In 2008, we studied and analyzed behaviors of a sound robot and a housefly [11] and [1]. In 2009, we have shifted our attention to robustness as an important characteristic of both biological and engineering autonomous systems. We designed a new autonomous robot with LEGO Mind storm [6] and also started a new experiment on the moving oil droplets with larger droplet sizes [5].

## 1 A New Principle

A difference between living and non-living is the presence of autonomy. Autonomy is necessary for agents to take actions and become cognitive. Whereas a complex machine cannot create its own motivation or behavior without being controlled from outside by a designer, simple organisms can decide what to do and see spontaneously. In this sense, living systems are autonomous compared to systems made up of non-living matter. Understanding autonomy is thus important in perceiving differences between living and non-living.

In previous studies, we proposed two guiding principles for simulating autonomy from artificial life studies. One is a form of self-tuning

sensoricoupling referred to as "autonomous coupling" (AC) [7], and the other is chaotic itinerancy induced by self-movement, referred to as "Embodied Chaotic Itinerancy" (ECI) [9].

Another characteristics we have focused on is robustness. Robustness can be defined as a property that allows a system to maintain its functions against internal and external perturbations[10]. This property is present in biological systems and is highly desired in engineered systems. On this robustness issue, we have previously studied simulation models and proposed a new principle called "Homeo dynamics" [8]. A system changes the parameters or boundary condition to adapt to the environment. In doing so, a system dynamically organizes its own parameters. This leads to a peculiar state that we call the homeodynamic state.

Based on these ideas, we develop the idea of autonomy and robustness in both natural and artificial systems, which is the aim of this project. Autonomy is no more mere randomness driven by a chaotic dynamics. Our concern should be with embodiment that mediates autonomy. Embodiment does not simply mean possessing a physical body, but must also incorporate the coordinated self-organization of behavior structures, which is robustness. This project will use a robotic experiment, a fly experiment and chemical experiments to test this idea.



Figure 1: Appearance of the robot MIURO [1]



Figure 2: A fruit fly in a cage [11]

## 2 Methodology

### 1. year 2008

ECI was tested with a commercial robot called MIURO, who plays music from an ipod on its top and synthesizes dance styles. In order to examine the ECI idea in a natural system, we analyzed the explorative behavior of a fly in a shallow closed cage. 1) Miuro plays music and its movement pattern is controlled by a remote PC. We have designed the program that generates ECI with MIURO. 2) *Drosophila* and the housefly in a cage was used here. Sugar drops are placed in several places in a cage and we quantitatively study the exploration patterns of the flies. Using a *Drosophila* mutant with a different memory capacity, we analyze the relationship between movement

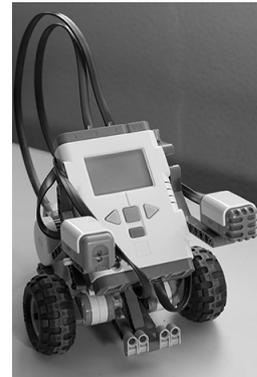


Figure 3: The Lego Mindstorms platform[6]

and memory capacity.

### 2. year 2009

Robustness was examined with two artificial mobile systems; a mobile robot and a self-moving oil droplet[3]. 1) A robotic platform is the Lego Mindstorms NXT(see figure 3), which is a modular robot assembled from many elements such as motors, sensors and structural modules. 2) An oil droplet system consists of neat oleic acid oil (NuChek Prep, Elysian, MN) and the alkaline water at pH 11. Also nitrobenzene (Kanto Chemical Co., Inc.) at 0.5 M was added to the oleic anhydride to stabilize the oil phase.

## 3 results

### 3.1 Experimental Robotics1

We introduced a third time scale in the robot. Whereas the time scale of the transition period of the neural network is set at around 5msec (NTS), the robot and computer need about 100 msec to communicate (RTS). Directly connect-

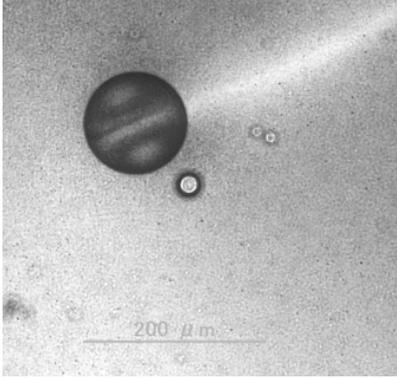


Figure 4: Characteristic convection flow pattern is visible in the moving droplet.[5]

ing these two time scales would not allow for any correlation between music and movement. Thus about 30 msec is needed to sample the state of the neural network and use this state to create a movement (MTS). The mutual information metric was used to characterize chaotic itinerancy of the dancing pattern[2].

### 3.2 Experimental Robotics2

A task of the LEGO robot is to move toward a target area in its environment, where one light source and one sound source are located at the same position. We examined the three sets of experiments ( a light only condition(L), a sound only condition(S) and a light and sound condition (LS)), to see how different modules for L and S are coupling/de-coupling each other. We see that the behaviours are not naturally mixed to compensate for each other's limitations. Instead, we see that the performance of LS is much lower than L but higher than the S condition under a certain noisy environment.

### 3.3 Experimental flies

Exploration activities of a fly were observed with video systems in the experiment using flies and a glass cage. We found that the flies show anomalous diffusion with or without food [11]. Also, using a mutant of *Drosophila* with a smaller storage capacity, we studied how movement pattern changes, but the memory capacity did not alter the pattern [4]. In particular, the organization of self-avoiding areas is observed, where the mutant flies avoid to go.

### 3.4 Oil droplet experiment

We analyzed the size dependency of the droplet motion. The larger droplets travel a longer distance and have the longer life time. A droplet does not move with a constant speed but often changes its speed and direction. In particular, a droplet repeats "stop" and "go" motion while moving around. the interval distribution obeys the power law. Therefore, it is not a simple Markovian process but is biased by some memory effects. We observed the similar memory effect in analyzing house flies [11, 4]. When the droplet shows a relatively straight motion. the size sustains a horseshoe shape while moving. The auto correlation function was computed by using the spatial position, and it shows the power law behavior.

## 4 Conclusions

The important messages of this project are the followings.

- 1) In natural and artificial systems, autonomy could be understandable in terms of coupling /de-coupling dynamics. All the experiments here clearly demonstrated the property.

A future work is to study a system with parallel coupling/decoupling channels.

2) In natural and artificial systems, robustness is a unique characteristic which requires a new theory. Homeo-dynamics is one such candidate. Robustness is brought about by self-adjustment process between a system and the environment. Understanding how robustness exists at different levels of a system is not a straightforward task. A simple robot experiment can be a useful platform for the study of robustness.

3) Organizing inner time scales and studying their hierarchical structure is a necessary future work. By changing those time scales in the LEGO robot, we are now studying the change of the performance and the degree of robustness.

## References

- [1] Aucouturier, J.-J. and Ogai, Y. and Ikegami, T., Using chaos to trade-off synchronization and autonomy in a dancing robot, Trends and Controversies, IEEE Intelligent Systems 23 274-85 2008.
- [2] Aucouturier, J.-J. and Ikegami, T., The Illusion of Agency: Two Engineering Approaches to Compromise Autonomy and Reactivity in an Artificial System Adaptive Behavior, Oct 2009; vol. 17: pp. 402 - 420.
- [3] Hanczyc, M., Toyota, T., Ikegami, T., Packard, N. and Sugawara, T. " Chemistry at the oil-water interface: Self-propelled oil droplets " J. Am. Chem. Soc.; (2007); 129(30) pp 9386 - 9391.
- [4] Horibe, N, "Adaptive Strategy of Memory and Learning :"(Master thesis, University of Tokyo, 2008).
- [5] Horibe, N. Hanczyc, M.M. and Ikegami, T., Shape and Motion dynamics in Self-Moving Oil Droplets, in the proceedings of the 3rd Mobiligence conference (2009) pp. 367-371.
- [6] Hubert, J. Matsuda, E., Silvermann, E. and Ikegami, T A Robotic Approach to Understanding Robustness, in the proceedings of the 3rd Mobiligence conference (2009) pp. 361-366.
- [7] Iizuka, H. and Ikegami, T., Simulated autonomous coupling in discrimination of light frequencies, Connection Science, 17 (2004) pp.283-299.
- [8] Ikegami, T and Suzuki, K From Homeostatic to Homeodynamic Self, BioSystems 91 388-400 2008
- [9] Ikegami, T., Simulating Active Perception and Mental Imagery with Embodied Chaotic Itinerancy, Journal of Consciousness Studies Vol.14 (2007) pp.111-125.
- [10] Silverman, S. and Ikegami, T. Robustness in artificial artificial life. In Proceedings of Complex '09 Conference, Tokyo, Japan, 2009.
- [11] Takahashi, H., Horibe, N., Shimada, M. and Ikegami, T., Analyzing the House Fly's Exploratory Behavior with Autoregression Methods ,J. Phys. Soc. Japan.77 84802 2008

# Emergence of mobiligence by environment-generation in flapping flight of butterfly

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## I. INTRODUCTION

The flapping flight of butterfly is an example of Mobiligence in which the environment is the generated flowfield. This research analyzes the mechanism to emerge butterfly's Mobiligence, i.e., the adaptive function in flapping flight of butterfly, from the viewpoint where the environment as the flowfield with vortex street induced by the flapping effects on the stability and/or maneuverability. Concretely, this study approaches to the problem by the biological analysis through experimental observations of living butterflies and by the systems engineering or synthetic approach [1]. This research project has carried out the following items.

**A. Biological Approach** In order to provide constantly the butterflies, *Parantica sita nipponica*, it is established to breed from eggs to imagoes. An experimental system with a low-speed wind tunnel is constructed to measure the motion and aerodynamic forces of actual butterflies quantitatively to evaluate the accuracy of numerical simulations. Anatomical understanding is advanced by using micro-XCT images to clarify their possible active motion.

**B. Engineering Approach** A 2D (two-dimensional) mathematical model is developed to achieve steady flight by focusing on butterfly's attitude. Recovery process after adding a large perturbation and maneuver based on the mathematical structure of steady flight have been investigated. A 3D mathematical model is constructed to analyze the stability of actual free-flying butterflies and so on. Its validity and accuracy are examined by comparing with the obtained experimental data. Moreover, a periodic flapping flight is realized by using the obtained model. It clarifies that the flowfield with vortex street induced by flapping and wing torsion caused by structural flexibility effect on the stability of flapping flight.

## II. EXPERIMENTAL OBSERVATION OF FLAPPING BUTTERFLY

An experimental system with a low-speed wind tunnel (Figure 1) is constructed. The motion and aerodynamic forces of actual butterflies, *Parantica sita nipponica*, are measured quantitatively. The butterfly is put into the wind tunnel, and

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the flapping-of-wings motion in the flow is captured by three high-speed video cameras. The joint angles of butterfly are calculated from the measured positions of typical points on the body in video images. Simultaneously, the forces applied to the butterfly, i.e. lift  $L$ , drag  $D$  and pitching moment  $M$ , are sensed by the measure. Freely flying butterfly is also measured for entire flapping flight motion.

The experiments of tethered butterfly were reported last year. Figure 2 illustrates a measured motion of a flapping period. Figures 3 shows flapping motion of three successive periods. The butterfly repeats this type of cyclic motion in a constant period when it continues the periodic flapping motion. This motion conserves same characteristics as the

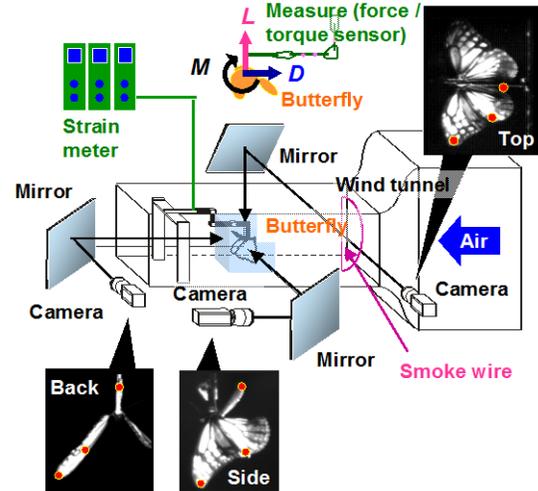


Figure 1: Experimental system

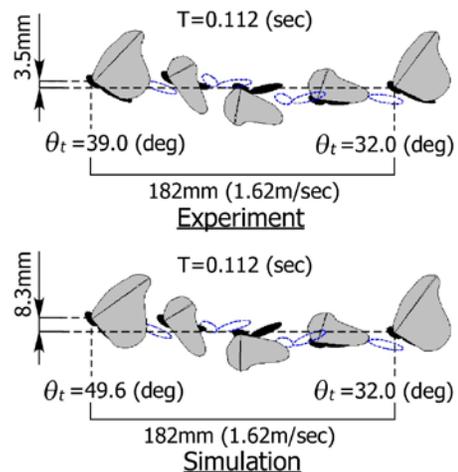


Figure 2: Measured motion of flapping butterfly (upper) and simulation of 3D model using measured joint motion (lower)

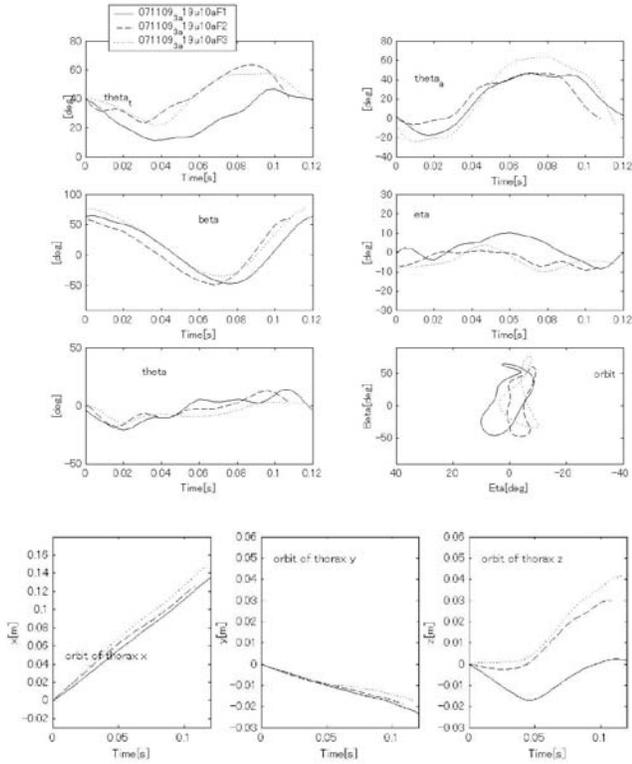


Figure 3: Measured motion of successive three flapping periods of flying butterfly

tethered case, e.g. the flapping angle is a cosine-like curve, the abdomen angle is its out of phase sinusoidal curve, and so on. Small variation of joint motion results in large change of thorax motion.

### III. ANATOMICAL OBSERVATION OF BUTTERFLY

To clarify the possible flight movements, morphology of thoracic muscles of a nymphalid butterfly, *Parantica sita niponica* is investigated using the micro-XCT (Comscantecno ScanXmate-A080S). The x-ray tube voltage, the tube current, and the minimum resolution (i.e. slice width and pitch) are adjusted 70 kV, 90 mA, and 18  $\mu\text{m}$ , respectively. Three-dimensional images are obtained by the software, Analyze. Skeletal structure of the thorax was also investigated to know points of attachment of muscles using the binocular after maceration in a 10% KOH solution for 1–2 days. The micro-XCT and microscope images are examined and muscles and sclerites observed are identified referring to the published thoracic skeletal structure and musculature of monarch butterfly, *Danaus plexippus* (Ehrlich and Davidson, 1961; Ehrlich, 1958) and a papilionid butterfly, *Luehdorfia japonica* (Emoto, 1983).

As a result, major indirect flight muscles including dorsal longitudinal muscles and dorso-ventral muscles of this species are identified from the reconstructed images of micro-XCT (Figure 4). From the observation of forewing base, small sclerites, basalare, subalare, pleural wing process, costal sclerite, 1st-4th axillary and postalar plate are identified (Figure 5). Some direct flight muscles such as basalar muscles



Figure 4: 3D images reconstructed with micro-XCT images of *Parantica sita niponica*

and subalar muscles are attached below the forewings via basalare and subalare, respectively. As known in other butterflies, *P. sita* basically uses indirect muscles for upstroke and downstroke and uses direct muscles for forward and rearward inclination of forewings.

### IV. DISCUSSION USING 2D MODEL

We have analyzed flight modes of two-dimensional flapping model based on the parameters of a danaid butterfly, *Parantica sita niponica*, and maneuverability of the model based on the knowledge of mathematical structure of possible flight modes. In particular, we have shown that flight mode transition occurs at particular parameters that are close to the adopted parameters of *Parantica sita niponica*. Moreover,

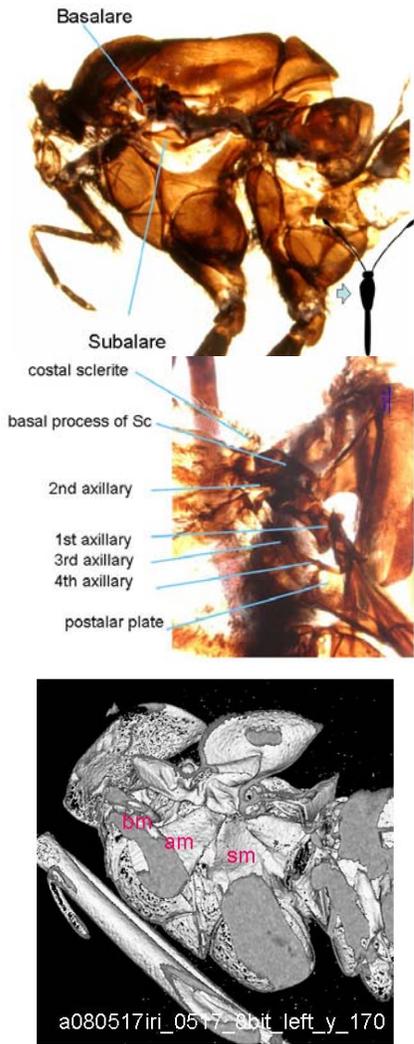


Figure 5: Exoskeletal thoracic structure dissected and exposed to 10% KOH and micro-XCT image of *Parantica sita niphonica*. Positions of basalare (BA) and subalare (SA) are shown.

using such structure, we demonstrate that a small change of a parameter can lead to a drastic transition between two different flight modes.

Insects create the environment due to vortices generated by flapping wings. They fly freely by interaction between wings using such environment, which is a characteristic for the insect's flight. An analytical theory of such environment has been constructed by focusing on far-field, and several applications were presented [3][4]. To compare such environments, a propulsion mechanism of flapping motion in creeping flow, which is an example of different environment, was studied [5].

Two-dimensional flapping model for *Parantica sita niphonica* has been constructed. Based on the model in ref. [7], we construct the model by assuming steady pitching angle due to an ideal control of pitching motion, by which steady flight is achieved (Fig.6). We have succeeded in studying maneuverability using interaction between vortices and flapping wings because the center of mass of this model is

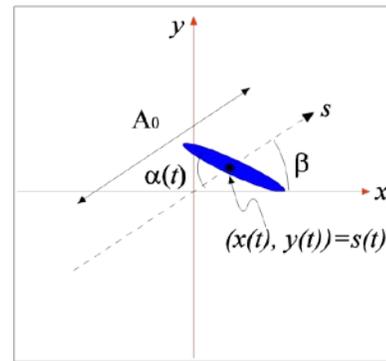


Figure 6: Two-dimensional flapping model. Angle  $\alpha(t)$  is a given function of time. Position of the center of the wing  $(x, y)$  moves according to the equations of motion under the hydrodynamic force.

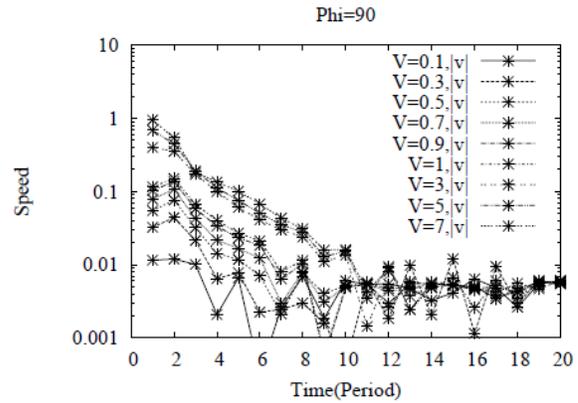


Figure 7: Recovery process from a large perturbation. Deviation of period averaged velocity from the steady state is shown as a function of time. Time scale of the recovery process is around ten periods.

stable. The parameter was adopted from the measured values of *Parantica sita niphonica* [8], although wing area is enhanced to adapt to two-dimensional model. Using this model, the following two results were obtained.

One is a recovery process of this model after adding a large perturbation by a vortex pair. The time scale of recovery process is around ten periods, and it is less dependent on the strength of the perturbation (Fig.7). On the other hand, it was revealed that there is a critical strength of the perturbation over which the recovery process experiences a transition. When the strength is represented by its characteristic speed, the critical value is close to the characteristic speed of the flow in the wake. When the characteristic speed of the perturbation is less than the critical value, the recovery process is described by a universal function.

The other is an application of the mathematical structure to maneuver. Adopted parameters are based on a real-life butterfly, and it is expected that an important mathematical structure related to animal flight be embedded. To investigate this, flight velocity under the change of the following parameter is analyzed: 1) gravity acceleration  $g$ , 2) flapping amplitude  $A_0$ , and 3) stroke-plane angle  $\beta$ . It is revealed that critical values of the parameters for the transition of flight are

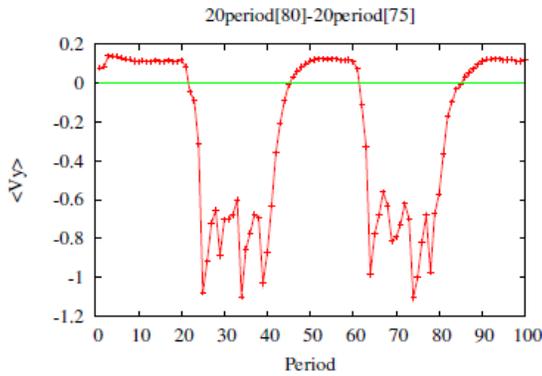


Figure 8: An example of flight maneuver. Vertical velocity is shown as a function of time. Stoke-plane angle  $\beta$  is changed 5 degrees every 20 periods. Cruising flight and descending flight is changed according to the slight change of  $\beta$ .

close to the adopted parameters, and flight mode changes from (almost) cruising flight to a descending flight. This fact suggests that flight-mode transition can be caused by small change of parameter, which can be used for maneuver. Here we demonstrate this maneuver by changing  $\beta$  between 80[deg](adopted value) and 75[deg] every 20 periods.

In Fig.8, period-averaged velocity is shown as a function of time. It takes just a few periods to switch from cruising flight to descending flight, while it takes about ten periods to converge to the steady state when switching from descending flight to horizontal flight. The reason is vortex pattern: in the first few periods, generated vortex pattern is upside-down from the pattern in the steady state. If we can find out a flapping pattern that suppresses generation of such vortex pattern, we may cause the transition more rapidly.

## V. DISCUSSION USING 3D MODEL

The 3D mathematical model using a panel method has been constructed. Its arithmetic precision has been improved by modification in the computer code. The joint motion of the actual butterfly of the upper in Figure 3 is substituted into the 3D model. The numerical result of the lower in Figure 3 almost duplicates the measured free flight motion. The obtained 3D model is accurate because other existing models cannot duplicate the measured free flight motion. Using this 3D model, we conclude the free-vortices in the wakes provide a type of stabilization effect as well as reference [1]. This result shows that the free-vortices induce the interaction with the feedback stabilization effect when wings in "body" exchange aerodynamic forces with "flow field". This is the feedback stabilization effect through the dynamic characteristic of the flow field, and it can be considered as an implicit control that is a common principle of mobiligence.

Passive wing torsion caused by structural flexibility is introduced to the model and its effect on the flapping-of-wings flight is examined [2]. Figure 9 shows two trajectories of

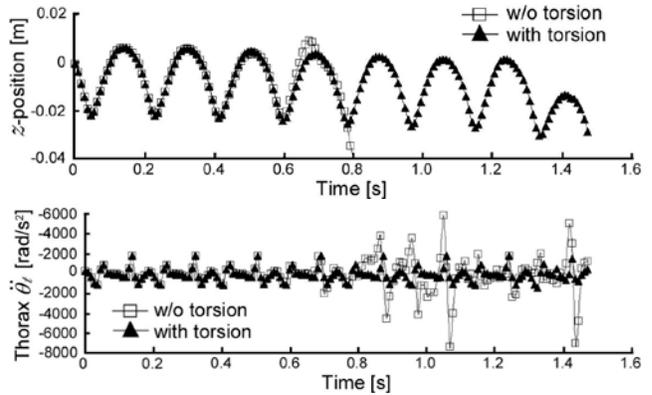


Figure 9: Flapping-of-wings flights with/without flexible torsion: flying height of butterfly (upper) and pitching acceleration of thorax (lower)

flapping-of-wings flights. One has been obtained by the trajectory searching in the previous paragraph, and the other is obtained by the model with flexibly torsional wings. The flexibly torsional wings extend the stable flight for four more periods. Figure 9 lower shows that the oscillation of the thorax angle is reduced, especially when the butterfly is going down. The wing flexibly damps the pitching oscillation of thorax, where the oscillation may cause the butterfly falling. As the result, the instability of thorax reduced, and the flying period extended. Therefore, the flexible torsion may introduce the stability effect on the flapping-of-wings flight. This is the feedback stabilization effect brought by this system through the dynamic characteristic of the body. It can be considered as a kind of preflex [7] as well as an implicit control that is a common principle of mobiligence.

## ACKNOWLEDGMENT

The authors would like to express sincere thanks to Dr. Naomichi Ogihara of Keio University for the help of making XCT images of a butterfly.

## REFERENCES

- [1] K. Senda, M. Sawamoto, M. Kitamura, T. Obara, Towards Realization of Stable Flapping-of-Wings Flight of Butterfly, Int'l Symposium on Adaptive Motion in Animals and Machines, 2008, 62-63.
- [2] K. Senda, M. Sawamoto, M. Kitamura, T. Obara, Effects of Flexibly Torsional Wings in Flapping-of-Wings Flight of Butterfly, World Automation Congress, 2008, pp. 1-6.
- [3] M. Iima, Analysis of hovering insect in two-dimensional space, RIMS koukyuuroku (in Japanese), 1631, 98-106, 2009
- [4] M. Iima, Numerical models and theoretical models for insect flight, Proceedings of workshop PPM2008 (in Japanese), 54-59, 2009
- [5] M. Iima and A. S. Mikhailov, Propulsion hydrodynamics of a butterfly micro-swimmer, Europhysics Letters, 85, 44001, 2009
- [6] M. Iima, Mathematical analysis of flight and swimming, Abstract of JSIAM meeting 2009 (in Japanese), 1802, 2009
- [7] M. Iima, A two-dimensional aerodynamic model of freely flying insects, J. Theor. Biol., 247 (2007) 657-671.
- [8] K. Senda, M. Sawamoto, M. Kitamura, T. Tanaka, Stabilization of Flapping-of-Wing Flight of Butterfly. *Considering Wakes in Bio-mechanisms in Swimming and Flying*, Springer, 2007, 193-204.
- [9] M. Iima, N. Hirai, and K. Senda, Recovery process from large-perturbed flapping flight of a two-dimensional flapping model for Parantica sita: a numerical study, Proceedings of JSFM 2009 (in Japanese), 2009

# A study on adaptation to environments in a network of dynamical elements

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**Abstract**—Against the unexpectedly changing environment, the human and the animal have to decide the optimal action for the survival. The typical example is to walk to the better environment, The central nervous system is an extremely efficient information processing device for this purpose. Therefore, we need to clarify the essence of the underlying mechanisms. The key feature is that the state of neurons at the nodes and the synaptic weights interact with each other via learning mechanisms. As such a system, we first investigate co-evolving dynamics in a weighted network of phase oscillators. It is found that this system exhibits three kinds of asymptotic behavior: a two-cluster state, a coherent state with a fixed phase relation, and a chaotic state with frustration. Next, we demonstrate that a network organized under spike-timing dependent plasticity (STDP), not only is capable of memorizing the activity patterns of the external stimulus, but also exhibits a systematic transition behavior among the memorized patterns in response to uniform external synchronized spikes. Finally, we consider the recurrent infomax, which maximizes the information retention and thereby minimizes the information loss through time in the recurrent network. Numerical simulations demonstrate that recurrent infomax provides a simple framework explaining for a wide range of phenomena observed in in vivo and in vitro neuronal networks. On the basis of these findings, we will explore the essential mechanisms of neuronal systems for emergence of adaptation through interaction among the body, brain and environment.

## I. INTRODUCTION

The central nervous system is an extremely efficient information processing device to realize high adaptability to the environment for the survival. As the underlying mechanisms, the synaptic plasticity such as Hebbian learning is very important[1], [2]. This activity-dependent synaptic plasticity is based on the memory function. In this context, we have mainly studied three closely related subjects.

## II. CO-EVOLUTION OF PHASES AND CONNECTION STRENGTHS IN A NETWORK OF PHASE OSCILLATORS

The first one is to elucidate the types of behaviors that can emerge in neuronal systems with various lean-

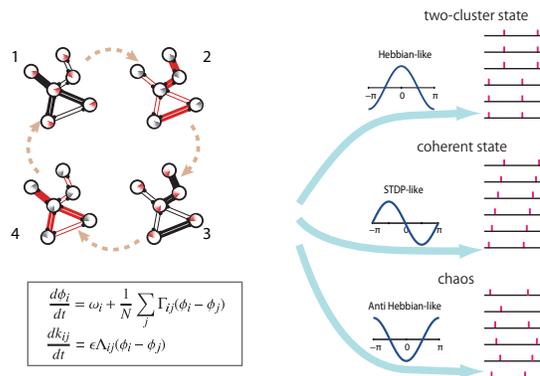


Fig. 1. A schematic illustration of co-evolution of both phase oscillators and network connections. 1. The phase pattern causes the structure of the weighted network to change. 2. The change undergone by the weights causes a new phase pattern to appear. 3. The change of the phase pattern results in further modulation of the weights of the network. 4. This process repeats. Note that in the actual process the phases and connections co-evolve simultaneously, not in a step-by-step manner.

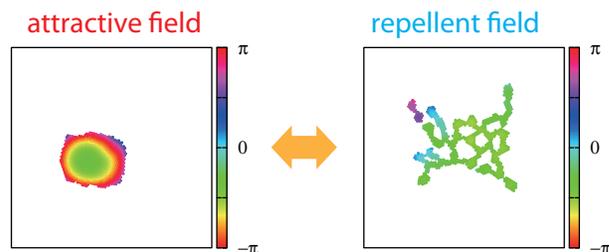


Fig. 2. Two typical structure of collected movable phase oscillators. The system tends to form a simple circle structure and a tree-like network one in response to the good and bad environment, respectively. The phase of each movable oscillator is denoted by the color.

ing rules and the functional role played by the evolution of the synaptic weights. Among many typical types of behavior, limit-cycle oscillation is widely observed in real neuronal systems, and coupled limit-cycle systems often generate a rich variety of collective behavior. Furthermore, limit-cycle oscillation is structurally stable, and it can be described by a simple model of phase oscillator that is mathematically tractable. Therefore, it

is reasonable to first consider a limit-cycle oscillator as the dynamical unit in the neuronal network.

Therefore, we investigate the co-evolving dynamics in a weighted network of phase oscillators, in which the phases of the oscillators at the nodes and the weights of the links interact with each other. Depending on the nature of the evolution of the coupling weights, this system can exhibit three distinct types of dynamical behavior: a two-cluster state, a coherent state with a fixed phase relation, and a chaotic state with frustration (See figure 1). This system exhibits a two-cluster state and a coherent state with a fixed phase relation when the dynamics of the weights are qualitatively similar to typical learning rules in neural network specified by the Hebbian and the spike-timing dependent plasticity rules, respectively. A chaotic state is realized in the case that the dynamics of the weights and phases are frustrated [4]. A more complete characterization of these three states is provided by the mutual information between the initial and final phase patterns and the entropy of final phase pattern. As a result, the mutual information is largest for the coherent state. Because the mutual information is the information that the initial and final states share, the initial phase relationship among the oscillators is most easily inferred from the final one in the case of the coherent state. This suggests that the coherent state can be interpreted as representing a memory of the phase pattern. In context of neural networks, which represent a typical example of the type of co-evolving system to which our model may be applicable, such sequential neural activity embedded in a network organized under STDP learning, has been studied both theoretically and experimentally with regard to the temporal neural coding. For the two-cluster state, the situation is qualitatively similar, except that the entropy is much smaller. This is because the allowed states of an oscillator belonging to the two clusters is restricted to only two possibilities. Therefore, this state is capable of representing a memory of binary data. As stated above, this state is organized under a kind of like-and-like rule. Even though at the present time we cannot give an example of this kind of chaotic state observed in real systems, we believe that such chaotic behavior will be seen in some type of co-evolving systems when compared with our model.

As an extended version of the above model, We propose a model of movable phase oscillators coupled by adaptive connections and investigate the emergent collective behaviors realized by the coevolving dynamics of the phases and the positions of the oscillators.

The system exhibits four distinct types of asymptotic states: an aggregate, a repulsive, a treelike, and a disconnected islets one. Interestingly, we found that the system drastically changes its formation of oscillators in adaptation to changing environments as seen in Figure 4.

### III. A ROLE OF UNIFORMLY SYNCHRONOUS INPUTS

Next, we consider a network of spiking neurons, in which the excitatory and inhibitory neurons are synaptically coupled each other. We assume that the excitatory synaptic strength are modified according to the STDP rule, whereas a globally uniform inhibition without modification of learning is included in an all-to-all manner [12].

We employ two types of controllable external inputs. One is a stimulus input, in which an initial stimulus-pattern and a training stimulus-pattern are presented during a trial and a learning session, respectively. For learning, we use a simple training stimulus-pattern, in which this pattern is divided into three parts consisting of firing patterns referred to as A, B and C, in which each composed of a particular set of active neurons. These neurons that are active for a given pattern fire periodically, and in each pattern, there are certain fixed phase relationships among the active neurons. During learning, these three patterns are presented as the stimulus input in the fixed order (A,B,C,A,B,C...). This can be regarded as representing a certain external sequence of events that the network is to learn, in other words, the causality of certain external events.

The other type of controllable input is an activation input, which projects to all neurons uniformly. This input is introduced to examine the effect of synchrony on the neuronal dynamics. This uniform background input serves to activate the entire network and to allow each neuron to be in a firing state under suitable conditions. There are two modes of neuronal activity for the activation input: asynchronous and synchronous modes. During learning, the activation input is always in the asynchronous mode. To remove the influence of firing rate modulation, in both modes, the average firing rate is set to the same constant value.

We first examine the case in which the activation input is initially set in the asynchronous mode, with the level of the total current such that the neurons are in an active state in response to an appropriate stimulus input and maintain an active state through recurrent excitatory synapses organized under the STDP. Figure 3a illustrates some typical activity patterns displayed

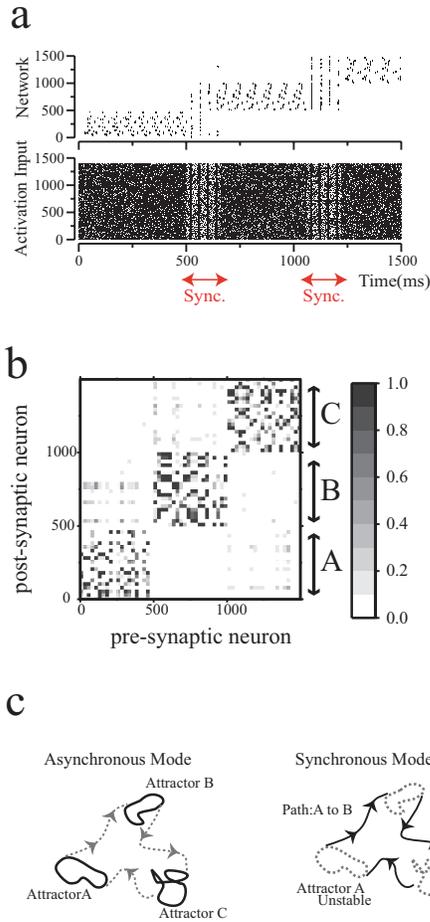


Fig. 3. Typical effect of a uniformly synchronized spike input on the network of spiking neurons organized under the STDP learning rule. a. Synchrony-induced switching behavior of the network realized through the STDP learning rule. b. Grayscale plot of the normalized strengths of excitatory synapses between neurons after the STDP learning. c. Interpretation of the synchrony-induced switching behavior from the point of view of dynamical systems.

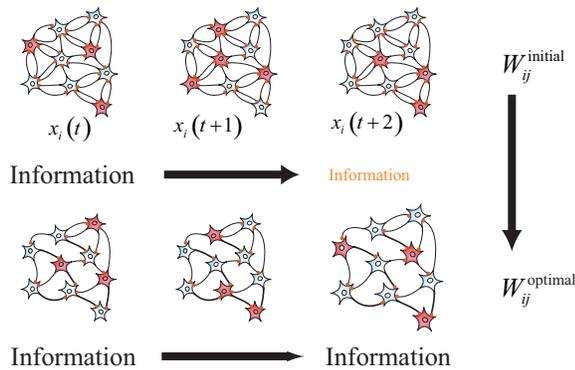


Fig. 4. Basic ideas of recurrent Infomax. Maximizing the mutual information between the state of the network at time  $t$  and  $t + 1$  reduces the information loss through time.

by the network (top) and the activation input (bottom) as rasterplots. First, the network exhibits the pattern A, which is stable when the activation input is in the asynchronous mode. Thus, in this case, the network exhibits ordinary associative memory. In Figure 3b, we can see clearly that three diagonal blocks of major synaptic connections, which are formed by the three basic stimulus patterns (A,B,C), enable the network to retrieve each pattern in an associative manner. In addition, there are three off-diagonal blocks of weak synaptic connections arising from the less frequent transitions among the stimulus patterns. Because the synaptic connections for transitions are relatively weak, under ordinary conditions, each individual pattern is sufficiently stable that no transition among patterns occurs.

Interestingly, Figure 3a demonstrates that a brief period of synchrony in the uniform activation input can enhance this weak effect embedded in the synaptic matrix and can thereby cause a transition from the one pattern to another. Therefore, when the activation input is switched for a brief time to the synchronous mode, a transition from the pattern A to the pattern B occurs. Hence, the retrieval of a learned sequence in the presented order can be triggered by globally uniform synchronous inputs. From the perspective of dynamical systems, when the network is activated by a uniformly asynchronous spike input, the system possesses some attractors formed by the STDP learning rule (Figure 3c left). However, a brief uniformly synchronous input activates the paths between attractors, leading to a transition to the next pattern in the learned order (Figure 3c right).

#### IV. INFOMAX FOR RECURRENT NEURAL NETWORKS

The neuronal system is an efficient information processing device to take better action for survival. However, the information coding in the brain is still a controversial issue, particularly, how does multiple neurons work in concert to realize specific brain functions? The principle of information maximization (Infomax) [7], which maximizes the information transmitted from the input to the output in the feedforward network, is effective for a learning mechanism the stimulus selectivity of the neuron to visual stimuli. Although Infomax is one of the plausible candidates for learning mechanisms, no recurrent connection was taken into account [11]. However, the existence of the recurrent connection is inevitably essential to realize the higher brain functions such as adaptation and decision making.

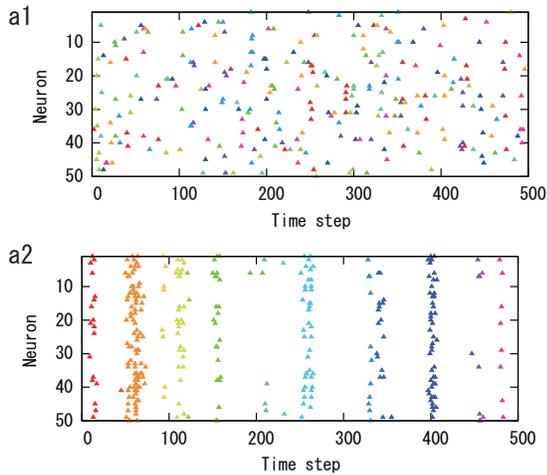


Fig. 5. Spontaneous activity of the recurrent network with  $p_{\max} = 0.5$ . (a1,2) Individual bursts in the spontaneous activities before (a1) and after learning (a2) are indicated by different colours. The bursts before learning were short and frequently interrupted by the steps without firing, whereas the bursts after learning had much longer duration.

Therefore, we will try to theoretically extend Infomax to the case of recurrent networks and we named this extended theory Recurrent Infomax. Recurrent Infomax maximizes the information retention, thus, minimizes the information loss through time in the recurrent network as shown in Figure 4.

We found that, in response to visual stimuli of natural scenes, the Recurrent Infomax organized the initial random network into a feedforward network with simple cell-like output neurons [8]. More interestingly, in the case of spontaneous firing state without external input, the resultant network exhibits the cell assembly-like and synfire chain-like activities [9] and the critical neuronal avalanche [10]. Figure 5 shows the typical firing patterns of network after leaning and the frequency distribution of the burst size.

## V. CONCLUSIONS AND FUTURE WORKS

In summary, we have first investigated co-evolving dynamics in a weighted network of phase oscillators in which phase oscillators at the nodes and the weights of their links interact and co-evolve. We found that this system exhibits three distinct types of dynamical patterns: a two-cluster state, a coherent state with a fixed phase relation, and a chaotic state with frustration. Because of its structural stability, it is believed that our model captures the essential characteristics of a class of neural networks. The second results suggest that synchronous spikes may act as a signal in biological systems, serving to link learned sequences of actions in

response to some external stimuli. We believe that some experimental results can be more clearly reinterpreted using our results. Finally, we demonstrated that the emergent of the simple cell-like stimulus selectivity, the spontaneous synfire chain-like activity and neuronal avalanche were explained in by the Recurrent Infomax in a unified way. On the basis of the above findings, using the novel experimental methods such as brain machine interface and cultured neural systems, we will study the adaptation mechanism through the interaction between environments and neuronal systems in the near future.

## VI. ACKNOWLEDGMENTS

I would like to thank T. Tanaka, M. Nomura and T. Aoki who participated in this study.

## REFERENCES

- [1] D. O. Hebb, *The Organization of behavior: A Neuropsychological Theory*. Wiley, New York, 1949.
- [2] G. Q. Bi and M. M. Poo, "Synaptic modifications in cultured hippocampal neurons: dependence on spike timing, synaptic strength, and postsynaptic cell type," *J. Neurosci.*, vol. 18, pp. 10 464–10 472, Dec. 1998.
- [3] H. Cateau and T. Fukai, "Local synchrony formed by spike-timing-dependent plasticity working on asynchrony-favoring neurons," *Neurosci. Res.*, vol. 58, p. S53, 2007.
- [4] T. Aoki and T. Aoyagi, "Co-evolution of phases and connection strengths in a network of phase oscillators," *Phys.Rev.Lett.*, vol. 102, Issue 3, pp. 034101, 2009.
- [5] E. Salinas and T. J. Sejnowski, "Correlated neuronal activity and the flow of neural information." *Nat. Rev. Neurosci.*, vol. 2, pp. 539–550, 2001.
- [6] G. Q. Bi and M. M. Poo, "Synaptic modifications in cultured hippocampal neurons: dependence on spike timing, synaptic strength, and postsynaptic cell type." *J. Neurosci.*, vol. 18, pp. 10 464–10 472, 1998.
- [7] R. Linsker, "Self-organization in a perceptual network," *Computer*, vol. 21, no. 3, pp. 105–117, 1988.
- [8] A. J. Bell and T. J. Sejnowski, "An information-maximization approach to blind separation and blind deconvolution." *Neural Comput.*, vol. 7, no. 6, pp. 1129–1159, 1995.
- [9] M. Abeles, *Corticonics*. Cambridge: Cambridge. Univ. Press, 1991.
- [10] J. M. Beggs and D. Plenz, "Neuronal avalanches in neocortical circuits," *J. Neurosci.*, vol. 23, no. 35, pp. 11 167–11 177, Dec 2003.
- [11] T. Tanaka, T. Kaneko and T. Aoyagi, "Recurrent infomax generates cell assemblies, neuronal avalanches, and simple cell-like selectivity ." *Neural Comput.*, vol. 21, no. 4, pp. 1038–1067, 2009.
- [12] T. Aoki and T. Aoyagi, "Synchrony-induced switching behavior of spike pattern attractors created by spike-timing-dependent plasticity." *Neural Comput.*, vol. 19, no. 10, pp. 2720–2738, 2007.

# Basic strategy for trajectory planning in human movements

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**Abstract**—In order to understand the design of animal movements that exploit redundant degrees of freedom of the body, we have analyzed human walking and locust jumping from the view point of joint coordination, a.k.a, joint synergy. The results of human walking have shown that joint synergy is exploited during walking especially at some critical points to stabilize walking, such as the moment of touch down and the moment when the toe passes its lowest position during leg swing phase. The analysis of locust jumping have also suggested that the body rotation is suppressed by joint synergy. In this report, I explain the outline of these results and explain that the joint synergy observed in locust might be realized by a simple intrinsic control.

## I. INTRODUCTION

Bernstein argued that dexterity is the ability to manipulate redundant degrees of freedom. He also explained “skilled smith’s hammer hits a given target correctly but his joint trajectories are not constant but show variability”, and pointed out that skilled movement shows high accuracy by exploiting redundancy at some critical points to accomplish a task, on the other hand, the movement shows variability at other points. This observation implies that the variability could bring a cue to understand how our brain constrains and utilizes the multiple degrees of freedom of our body in order to accomplish a task. In the following sections, I introduce our recent results of the analyses of human walking and locust jumping from the view point of exploitation of multiple degrees of freedom, in other words, joint synergy in this study.

## II. JOINT SYNERGY IN HUMAN WALKING

In previous studies we have obtained some results that indicate that the leg swing trajectory during human walking is near from the optimal one that minimizes energy cost under the condition of leg retraction at the end of swing [1]. Some studies also have shown that the leg retraction observed in the end of swing phase makes soft landing of the foot possible, which contributes to

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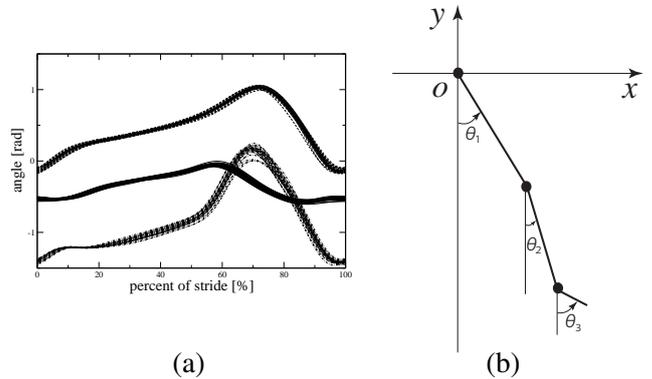


Fig. 1. Joint trajectories during human walking. In (a), lines show the angles of hip, knee and ankle joint, respectively, from the above at 0% of stride time. The horizontal axis shows the normalized stride time and 0% is the start of stance phase. (b) shows the definition of joint angles.

stabilizing walking [2]. If such leg retraction is really an important point to realize stable walking, our nervous system would not allow random variance of leg joints and constrain the variance during leg retraction or at the moment of landing. Furthermore, it would be possible that some joints cooperate to control the foot movement at such moment. In our study, we analyzed how joint synergy works at every moment during walking in order to investigate the underlying control scheme to realize stable walking[3], [4].

### A. Experimental method

Subjects were four females in their twenties with no disorder in lower extremities. We measured the leg trajectories of the subjects who equipped reflective markers at the hip, knee, ankle and toe, and walked on a treadmill at 3, 4.5 and 6 km/h. The trajectories were recorded by a motion capture system (Himawari SP200, LIBRALY co.) by 200 fps and smoothed by a 6th-order low-pass Butterworth filter with cutoff frequency of 6 Hz.

### B. UCM analysis

In this study, we modeled the leg as a simple three-link system that moves in a vertical plane

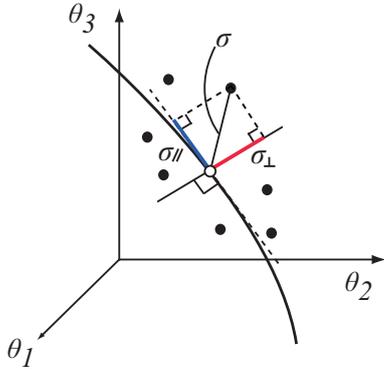


Fig. 2. Analysis of variance from the view point of the UCM. Axes show joint angles, closed circles show the joint angles at a specific stride time during walking, open circle shows the average, and curved line is the UCM that shows the solutions to realize the same toe position.  $\sigma^{\parallel}$  and  $\sigma^{\perp}$  show the parallel and orthogonal components of the deviation to the UCM, respectively. The former deviation does not change the toe position but the latter does.

(Fig. 1(b)), and analyzed the leg movement during walking as follows. The leg trajectory data  $(t) = (\theta_1(t), \theta_2(t), \theta_3(t))^T$  of 25 strides for each subject were normalized by the stride period, where the subscript  $i = 1, 2,$  and  $3$  show hip, knee and ankle, respectively. The average  $\bar{(t)} = (\bar{\theta}_1(t), \bar{\theta}_2(t), \bar{\theta}_3(t))^T$  of the 25 normalized data was computed for each subject, and the distribution of the deviation of joint angles  $\sigma^k(t) = {}^k(t) - \bar{(t)}$  was analyzed by the UCM method, where the superscript  $k$  indicates the  $k$ -th stride data (Fig. 2).

When slight change in joint angles  $\epsilon(t) = (t) - \bar{(t)}$  satisfies the following relation, it does not change the toe height  $y(\cdot)$  relative to hip from  $y(\bar{\cdot})$ .

$$\nabla y \cdot \epsilon = 0$$

The parallel component of the deviation of each stride data to the above  $\epsilon$  and its orthogonal component were computed and then we obtained the average of the amplitude of these values,  $\sigma^{\parallel}(t)$  and  $\sigma^{\perp}(t)$ , where the former shows the variance into the UCM direction and the latter shows the variance into the orthogonal direction to the UCM. When  $\sigma^{\parallel}(t)$  is larger than  $\sigma^{\perp}(t)$ , such distribution of the joint angles suggests that there is joint synergy that suppresses the deviation of the toe height. To judge the existence of the joint synergy, we define the degree of synergy  $S$  by

$$S(t) = \frac{\sigma^{\parallel}(t)}{\sigma^{\perp}(t)}.$$

By the definition,  $S > 1$  indicates the existence of joint synergy.

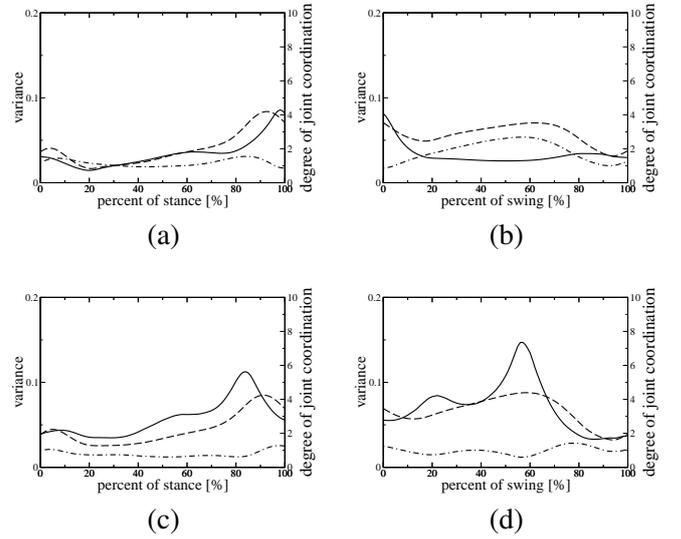


Fig. 3. The degree of joint synergy and the UCM components of variance respecting the toe position relative to the hip position. (a)(b) and (c)(d) show the degree of joint synergies that suppress the variance of horizontal and vertical toe position, respectively, and the variance components. (a)(c) and (b)(d) show the results for stance and swing phase. In (a) and (b), solid, broken, and chain lines show the degree of synergy  $S_x$ ,  $\sigma_x^{\parallel}$ , and  $\sigma_x^{\perp}$ , respectively. In (c) and (d), solid, broken, and chain lines show the degree of synergy  $S_y$ ,  $\sigma_y^{\parallel}$ , and  $\sigma_y^{\perp}$ , respectively. The walking speed was 4.5 km/h, and data are the average of the results of the UCM analysis for four subjects.

In this study, we computed four kinds of the UCM components,  $\sigma_y^{\parallel}$ ,  $\sigma_x^{\parallel}$ ,  $\sigma_{vy}^{\parallel}$ , and  $\sigma_{vx}^{\parallel}$ , for the UCMs on which the vertical and horizontal components of the toe position and velocity relative to the hip position are constants, respectively. Their orthogonal components,  $\sigma_y^{\perp}$ ,  $\sigma_x^{\perp}$ ,  $\sigma_{vy}^{\perp}$  and  $\sigma_{vx}^{\perp}$ , and degree of synergy,  $S_x$ ,  $S_y$ ,  $S_{vx}$ , and  $S_{vy}$ , were also computed.

### C. Experimental results

1) *Control of toe position:* Fig. 3 show the UCM components of the variance of the leg joint angles and degree of joint synergy that suppress the variance of the vertical and horizontal toe position relative to the hip position. Over the most of entire stride period,  $S_y(t)$  is always larger than 1 which suggests that the variance of the vertical toe height is suppressed by joint synergy. Except in the beginning of stance phase,  $S_x(t)$  is also larger than 1 (Fig. 3(a)(b)), which suggests that the variance of the horizontal toe position is also suppressed by joint synergy, however,  $S_x$  is lower than  $S_y$ , i.e., joint synergy works for the control of the toe height more than that of the horizontal toe position.

In stance phase,  $S_y$  becomes large just before the

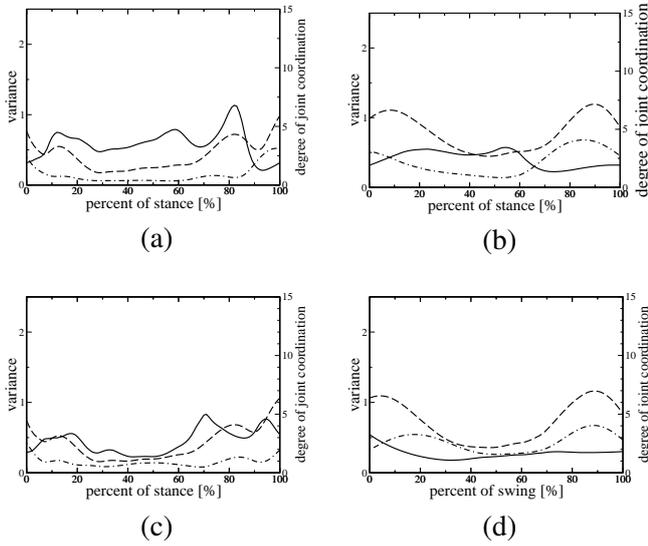


Fig. 4. The degree of joint synergy and the UCM components of variance respecting the toe velocity relative to the hip position. (a)(b) and (c)(d) show the degree of joint synergies that suppress the variance of horizontal and vertical components of toe velocity, respectively, and the variance components. (a)(c) and (b)(d) show the results for stance and swing phase. In (a) and (b), solid, broken, and chain lines show the degree of synergy  $S_{vx}$ ,  $\sigma_{vx}^{\parallel}$ , and  $\sigma_{vx}^{\perp}$ , respectively. In (c) and (d), solid, broken, and chain lines show the degree of synergy  $S_{vy}$ ,  $\sigma_{vy}^{\parallel}$ , and  $\sigma_{vy}^{\perp}$ , respectively. The walking speed was 4.5 km/h, and the results is the average of the results of the UCM analysis for four subjects.

start of double-support phase (around 83% of stance time) that indicates that the variance of hip height is suppressed by joint synergy for the touch down of contralateral leg (Fig. 3(c)).

In swing phase,  $S_y$  becomes especially high when the toe passes its lowest position from the ground (around 60% of swing in Fig. 3(d)), i.e., the toe height is precisely controlled by joint synergy, which would contribute to avoid accidental stumbling due to fluctuation of leg movement.

Just before touch down (after 95% of swing), all deviations,  $\sigma_x^{\parallel}$ ,  $\sigma_x^{\perp}$ ,  $\sigma_y^{\parallel}$ , and  $\sigma_y^{\perp}$ , decrease, which suggests that the variance of the toe position becomes small during leg retraction (Fig. 3(b)(d)). Most of these characteristics were also observed in other walking speed.

2) *Control of toe velocity*: Fig. 4 shows the UCM components of variance of joint angular velocities and degree of joint synergy that suppresses the variance of the horizontal and vertical components of the relative toe velocity to the hip position. In most of the entire stride period,  $S_{vx}$  and  $S_{vy}$ , are larger than 1, which suggests that the variance of the toe velocity is suppressed

by joint synergy. In stance phase,  $S_{vx}$  becomes large just before the start and the end of the double-support phase (around 20% and 83% of stance time), i.e., the horizontal speed of the hip is regulated by joint synergy at the moments.

Just before touch down (after 95% of swing), all variances,  $\sigma_{vx}^{\parallel}$ ,  $\sigma_{vx}^{\perp}$ ,  $\sigma_{vy}^{\parallel}$ , and  $\sigma_{vy}^{\perp}$ , decrease, i.e., the variance of the toe velocity at touch down becomes small. These characteristics were also observed in other walking speed.

#### D. Joint synergy during walking

The results of this study have shown some control points for human walking. The first is the control of the toe height when it passes its lowest position. When we build a legged robot, the design of a leg swing trajectory is an important point to avoid stumbling and realize stable walking. Our results indicate that the toe height is controlled by exploiting joint synergy especially at the moment when the risk of stumbling is high.

The second is the control of the posture at the start of double support phase. At the moment the height and the horizontal speed of the hip is controlled by joint synergy and the variance of leg posture and velocity of swing leg is lowered. These facts suggest that the posture at touchdown is precisely controlled by exploiting joint synergy, which would suppress the variance of the impact at touch down and improves the stability.

### III. POSTURE CONTROL IN LOCUST JUMPING

The jump of locust is propelled by hindlimbs within a few decade milliseconds. The force that the leg can generate is rotational force around joints, therefore, the body would rotate without precise planning of the combination of joint torques, however, the body rotation is effectively suppressed in jump of *Locusta migratoria* in most cases. Does it mean that the joint trajectories are precisely planned and realized or that the body rotation is suppressed by joint synergy? In order to consider this problem we investigated the locust jumping by the UCM analysis.

#### A. Experimental Method

The jumping movement of *Locusta migratoria* were recorded by a motion capture system (Himawari SP200, LIBRALY co.) by 1000 fps and the angles of body  $\theta_b$ , coxa-trochanter joint  $\theta_1$ , femur-tibia joint  $\theta_2$ , and tibia  $\theta_3$  (Fig. 5). The obtained data were smoothed by a 6th-order low-pass Butterworth filter with the cutoff frequency of 200 Hz. The jumping movements from the

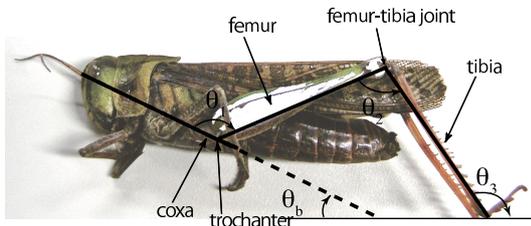


Fig. 5. Joints of locust.

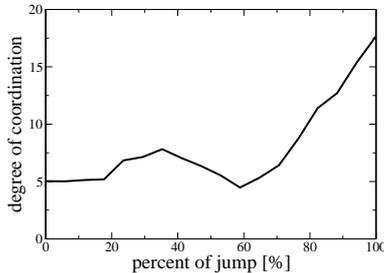


Fig. 6. Degree of joint synergy in locust jumping

takeoff of the forelimb to the takeoff of the distal end of tibia of hind limb were normalized by the duration and analyzed by the UCM method. In the UCM analysis, we computed the degree of synergy to set the body angle constant by joint synergy of  $\theta_1$ ,  $\theta_2$  and  $\theta_3$ . The analysis was done for four locusts and the results were averaged.

### B. Experimental results

Fig. 6 shows the degree of joint synergy  $S$  which keep the body angle constant and indicates that high joint synergy is observed during jump. In order to move by jumping, it would be disadvantage that the work to generate joint torque is transferred to the rotational energy of the body. The result indicates that the work done by muscles would be effectively transferred into the kinetic energy for jumping.

## IV. THE MECHANISM THAT BRINGS JOINT SYNERGY

The previous section have shown that the joint synergy to suppress the rotation of body is observed in locust jumping. When we observe the locust jumping, the rotation of body is not often observed even when their leg shows some slip during jumping. The jump movement takes less than 20 ms, therefore, it would be too short for nervous system to adjust the joint angles by feedback control. In fact, locusts seem to realize the joint synergy by a very elegant and simple way. The power for jumping is supplied by releasing the elastic energy stored in a semi-lunar organ at the

femur-tibia joint and apodeme in tibia. The center of the mass of a locust is located around the coxa, and when we assume that the friction at joints around the coxa is negligible and the propulsion torque is generated only at the femur-tibia joint, it can be mathematically proved that the center of mass is applied a force of a constant direction during jump and this prediction well explain the movement of the locust [5]. Under the same assumption, it is easily understood that the body would not rotate during jumping. Such mechanism of locust jumping seems to be attractive at the point that the some kind of joint synergy can be realized by a simple design of physical structure. Although the underlying mechanism of joint synergy in human walking has been unknown, it might also be realized by some physical structure, such as biarticular muscles that makes some constraints between two joints.

## V. CONCLUSION

In this article, we have introduced that joint synergy is exploited in human walking and locust jumping, and explained that the joint synergy found in locust jumping can be realized by a simple physical structure. Such intrinsic control that utilizes physical structure would be exploited in many basic movements, such as locomotion. Although it is usually difficult to judge whether some joint synergy is realized by the explicit control by nervous system or by intrinsic control like the example of locust jumping, investigating such mechanism would bring an important key to understand the tricks that living bodies have acquired through natural selection in order to react with environment adaptively.

## REFERENCES

- [1] A. Fujii, H. Suenaga, Y. Hashizume, and J. Nishii, "Variability of leg swing trajectories and their optimality," *Proc. of 4th International Symposium on Adaptive Motion in Animals and Machines*, pp. 173–174, Jun 2008.
- [2] M. Wisse, C. G. Atkeson, and D. K. Kloimwieder, "Dynamic stability of a simple biped walking system with swing leg retraction," *Lecture Notes in Control and Information Sciences*, vol. 340, pp. 427–443, 2006.
- [3] S. Kaichida, Y. Hashizume, and J. Nishii, "An analysis of leg trajectories of human walking from the view point of joint coordination," *Proc. of the 3rd International Symposium on Mobiligence 2009*, pp. 409–412, 2009.
- [4] S. Kaichida, Y. Hashizume, and J. Nishii, "An analysis of joint coordination during human walking," *Abstract of Progress in Motor Control 2009*, pp. A1–43, 2009.
- [5] M. Burrows and G. Morris, "The kinematics and neural control of high-speed kicking movements in the locust," *J Exp Biol*, vol. 204, pp. 3471–3481, 2001.

# Adaptation and emergence of biological function by environment-dependent-dynamical network in plasmodium of *Physarum polycephalum*

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**Abstract**—Plasmodium of true slime mold, *Physarum polycephalum*, is multinucleated unicellular amoeba-like organism. It crawls on environment with cell-thickness oscillation. Although the plasmodium seems to be peculiar, it is one of the ideal model organisms from viewpoint of "mobiligence."

Even when the plasmodium is divided into parts, each part behaves as a single oscillating cell without losing biological function. Therefore the plasmodium can be considered as a collective of units, i.e., coupled oscillators. On the other hand, the cell forms a network of tubular structure, inside which protoplasmic streaming is observed. The streaming act as interaction among the units. Interestingly, the morphology of the plasmodial network depends on environmental condition, as well as oscillation frequency. This suggests that the network morphology could affect the biological function to adapt to environment.

The network structures under various environment were analyzed by focusing on the network topology and morphology. We found that the plasmodium under repulsive condition forms tree-graph like network, extend tentacles with limited resource, i.e. protoplasm. In addition, it was revealed that the oxygen consumption is minimized with the tree-graph network topology. Contrarily, the plasmodium under attractive condition forms meshed network with fractal-like hierarchical bifurcated tubes, covers the surface of the nutrient rich medium by maximizing the contact area with it. For future work, we will reveal the mechanism of the adaptation by morphology by developing the simple model proposed in this study.

## I. INTRODUCTION

Most of biological organism have transportation network to distribute oxygen, nutrient and etc., into whole body. Animals including human have blood vessels network. Plants have leaf veins and vessels [1]. By expanding this to population, trail pattern by ant-foraging [2], road grid constructed by human [3], and power grid as man-made structures can be included as some of examples for transportation networks. The morphology of the networks depends on species and environment, which could affect each biological function. In this study, we investigate adaptation by transportation

network morphology by using plasmodium of true slime mold, *Physarum polycephalum*.

## II. PLASMODIUM OF TRUE SLIME MOLD AS MODEL ORGANISM

The cell size of plasmodium of true slime mold ranges from  $10\mu$  m to 1 m. Even if the single cell is divided into multiple parts, each part can be alive. On the other hand, multiple cells can fuse into a single cell to behave as a single individual. Ability of the cut & paste manipulation in the plasmodium results from unusual cell system, i.e., in which the plasmodium is multinucleated unicellular organism including thousands of nucleus in a single cell.

To maintain such a large cell body, the plasmodium developed a peculiar system in which the cell itself is a transportation network consisting of tubular structure. The tubular network is formed when the cell body spread into environment by oscillating cell thickness and crawling. The protoplasmic streaming observed inside the tubes transports nutrients, oxygen, organella, and etc., all over the cell body.

The morphology of the plasmodium changes depend on environment [4]. It shows thin sheet when the environment is nutrient-rich or the substratum is stiff (attractive condition). In contrast, it shows dendritic when the environment contains harmful chemicals or the substratum is soft(repulsive condition).

Our goal is to elucidate the adaptation behavior by morphology in the plasmodium. For this, (1) we abstract the characteristics of transportation network structure of the plasmodium, then (2) show effectiveness and functionality of the strategy of the environment-dependent morphology.

## III. ENVIRONMENT DEPENDENT MORPHOLOGY (YOKOTANI, TAKAMATSU) [4]

The morphology of the plasmodium was quantitatively investigated under various condition. Fig. 1 shows the morphology of the plasmodium after 8-hours cultivation according to the various environmental conditions such as concentration of attractants (oat flake extraction), repellents

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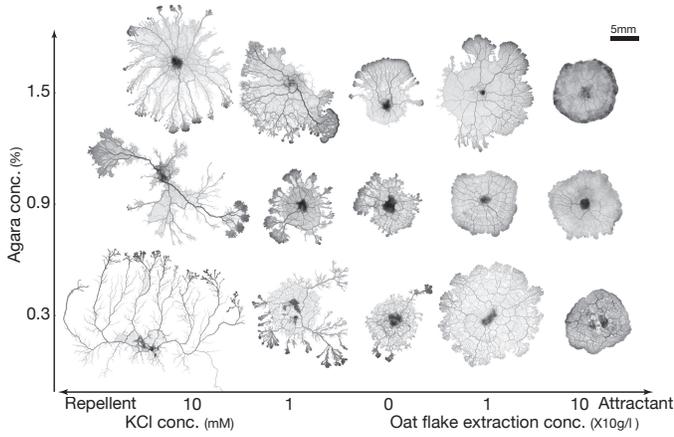


Fig. 1. Environment dependent morphology in plasmodium of *Physarum polycephalum* [4]. After 8 hours cultivation under constant temperature at  $25^\circ$  and humidity at RH85 %. Initial weight of plasmodia were  $0.005 \pm 0.001$  (g).

(KCl), and surface stiffness of culture media (concentration of agar). Quantitative analyses on morphology such as fractal dimension, circularity, area size, and flatness were performed. To quantification the local interaction between the plasmodium and environment, spread angle and contact angle of the tip portion of the plasmodium were estimated. These data were utilized for construction of network growth model later (§VII).

#### IV. ANALYSIS ON NETWORK TOPOLOGY (ITO) [5]

We only focus on network topology of tubular structure in this section. Vertices in the network were defined at bifurcation points. Edges were defined in the tubes connecting the both ends, i.e., the vertices. Then the connection relations were examined ([5]).

From the information on vertices and edges, we calculated number of vertices  $n$ , mean degree  $\langle k \rangle$  ( $k$  is number of edges the regarding vertex has), clustering coefficient  $C$ , mean path length  $L$  [6]. In addition to this, we also estimated meshedness coefficient  $M$  [7], which is useful to evaluate how densely the network has circle structure in two-dimensional network such as plasmodial network.

Significant examples are shown in Fig.2 for plasmodial networks in attractive condition and repulsive condition.

The mean shortest distance between any two vertices  $L$  indicates how widely the network spread. Fig.2(a) shows  $n$ - $L$  plot.  $L$  increases slowly depending on  $n$  in attractive condition, while it increases drastically at  $n = 2000$  in repulsive condition.

The meshedness  $M$  indicate density of cycle structure consisting of a polygon. Fig.2(b) shows  $n$ - $M$  plot.  $M$  is useful for estimation of number of edges in polygons composing the network. For example, the values are calculated as  $M = 0$  in tree graph, 0.15–0.25 in hexagonal-lattice, 0.3–0.5 in tetragonal lattice, and 0.65–1.00 in trigonal lattice. The plasmodial network would be close to hexagonal lattice

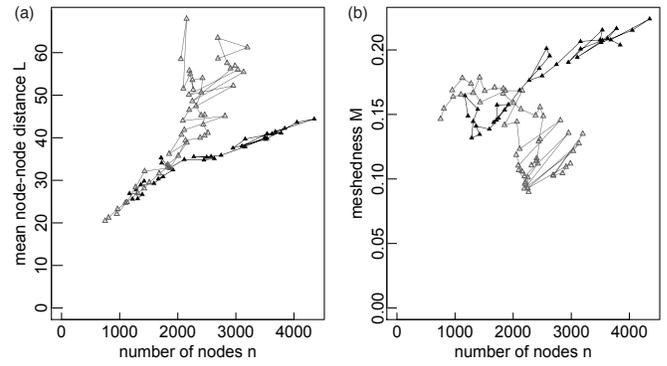


Fig. 2. Mean node-node distance and meshedness.(a) $n$ - $L$  plot. (b) $n$ - $M$  plot. Closed triangles and open triangles denote the data for 1.5 w/v% agra medium with 10 w/v% oat extract and 0.3 w/v % agar medium with 10 mM KCl, respectively. Lines are connected in order of time.

in attractive condition and tree-graph network in repulsive condition.

#### V. ANALYSIS ON NETWORK MORPHOLOGY (OKAMOTO) [5]

In planer network such as the plasmodium, interaction strength, i.e., tube diameter, and length between vertices could be important rather than degree and distance as number of paths. We analyzed the distribution of tube diameter and length in each plasmodial network. Under attractive condition, the tube diameter distribution seems to be scale-free or exponential distribution, continuous distribution from thin tube of high frequency to thick tube of low frequency, e.g., the network has fractal-like hierarchical bifurcated tubes. Contrary, under the repulsive or neutral condition, the distribution has continuous distribution in early stage but has a peak at 0.3–0.4mm in later stage. These may suggest that the nature of scale-free structure is embedded in the distribution of interaction strength. The structure is interestingly destroyed at repulsive condition. Further precise analysis including statistical test will be needed.

#### VI. SPATIO-TEMPORAL PATTERN (TAKAMATSU) [5]

The oscillatory cell of plasmodium is expected to have various spatio-temporal pattern depending on the network morphology. Spiral patterns with small wave length was observed at thin meshed network of attractive condition. Contrary, transversally propagated waves with long wave length was observed at thick -tube-network in repulsive condition. These observation will be compared with those observed in the network model proposed at the following §VII

#### VII. NETWORK MODEL (KAGAWA, TAKAMATSU) [4], [8]

The environment-dependent morphology of the transportation plasmodial network was verified using with a simple mathematical model. In §III, it was shown that the local interaction between plasmodium and environment depends on the environmental condition. Based on the observation, a network model, where vertices and edges growing on a

triangle lattice. It is assumed that the spread angles of the newly growing edges depends on concentration of nutrients or repellents, and the placed probability of the vertices connecting to the edges depends on stiffness of culture media. Fig.3 shows the simulation results, which shows good agreement with the Fig. reffig:morphology, suggesting that local interactions of the plasmodium with environment and the plasmodium itself emerges the global pattern of the entire body of the plasmodium.

Then spatio-temporal patterns depending on the network morphology were investigated by using coupled oscillator systems. A coupled oscillator system was constructed on a concentrically spread meshed network. Tree-like and meshed network were generated by varying the interaction strength of edges connecting vertices in radial and concentric directions. The system shows the similar spatio-temporal patterns depending on the network morphologies observed in §VI.

The combination of the network growth model and the coupled oscillator model would represent the behavior observed in the practical plasmodium. We will proceed to elucidate the mechanism of adaptation by the environment-dependent morphology described in the following sections by the simple mathematical model.

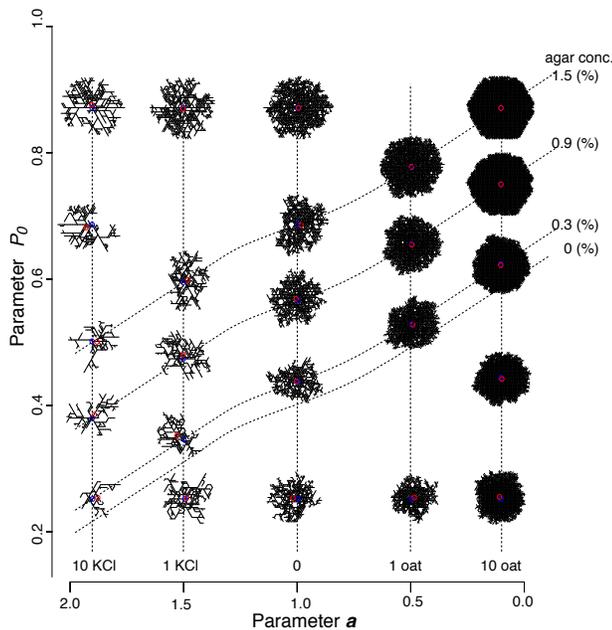


Fig. 3. Simulation results with the network growth model. Only edges are shown with lines. The diameter of the triangle lattice plane is 29; the maximum numbers of vertices and edges are 1519 and 4422, respectively. Blue circles show initial positions. Red circles show centroids of the final patterns. Dashed lines denote the parameter values for the experimental conditions.

### VIII. NETWORK MORPHOLOGY AND BIOLOGICAL FUNCTION (GOMI, HIRAI, ENDO, YOKOGANI, TAKAMATSU)

To understand how the morphology plays roles in the biological function, we measured the energy consumption (oxygen consumption per unit time) of the plasmodium with

the various network morphology under the other factors such as internal nutrient condition and culture periods fixed. Fig.4 shows the experimental result. Fractal dimension was taken as indices of network morphology. We showed that the oxygen consumption increases depending on the fractal dimension: The tree-graph like network under repulsive condition is the energy-saving one.

To look how the efficient network is generated, the relation among spatio-temporal patterns, tube growth, and the behavior was investigated. Fig. 5 shows the bifurcation diagram for the oscillation frequency (peaks of distribution of the oscillation frequency) and the trajectory of centroid position in neutral condition (in repulsive condition, the result is very similar). In early stage, the frequency distribution has a single peak, then bifurcates to multi-frequency. Corresponding to this, the plasmodium starts to move. Finally only the lowest frequency component remains, which is considered to be closely related to the thick tube formation. It could generate the efficient transportation in the tree-graph like network.

Under more complicated condition, the plasmodium shows more interesting behavior. Fig.6 shows a plot for the plasmodium placed at the boundary of two different environmental conditions: The ratio of the sizes in test area / total area are plotted to show which environment the plasmodium prefer. The plasmodium placed at the boundary of the two extreme conditions of attractive and repulsive never spread to the repulsive one immediately moves to the attractive one (Fig.6a). Contrary, the plasmodium placed at the boundary with small difference once moves toward one of the environment, then moves towards another one, and repeats this behavior alternately. It seems to hesitate to decide one on the choices immediately, however, finally the plasmodium selects one of those without hesitation. The hesitation behavior might relate to "mobilligence".

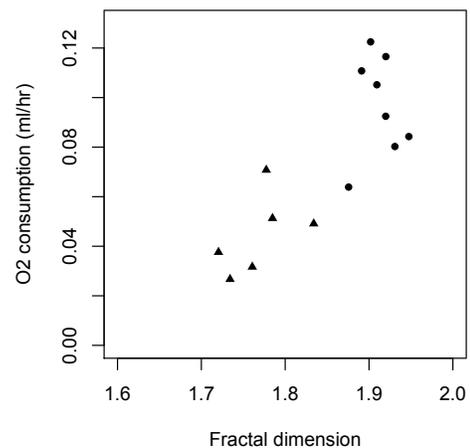


Fig. 4. Relation of oxygen consumption with fractal dimension in tree-structured plasmodium in 0.3 % agar medium (triangles) and mesh-structured plasmodium in 1.5 % (circles). Weights of plasmodium are  $0.10 \pm 0.01$  (g).

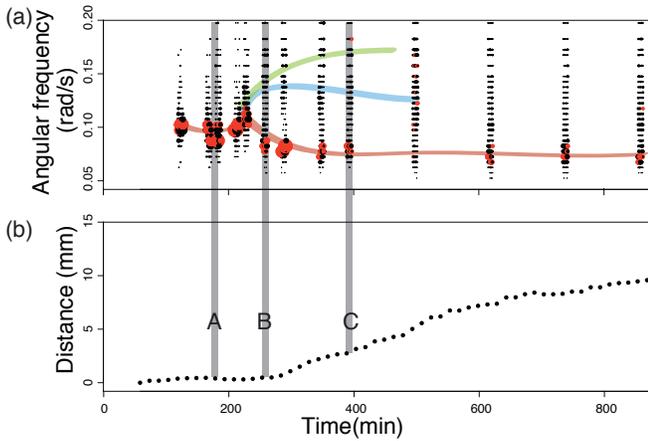


Fig. 5. Bifurcation of oscillation frequency (a) and trajectory of centroid position (b). (a) The density of oscillation frequency versus time were plotted with dots whose diameter are proportional to the frequency density. The large dots represent the main peaks in the histograms. Hand-drawing curves follows the primary, second and third peaks in the histograms. (b) Centroid position of the plasmodium calculated from the binary image was plotted. Origin was set when the plasmodium was set up at first. Plasmodium was cultured at neutral conditions, 0.9 w/v% agar medium without chemicals.

## IX. APPLICATION AND COLLABORATION (WATANABE, TERO, NAKAGAKI, MATSUMOTO, ARAFUNE)

We applied the plasmodial system to artificial systems on amoeboid modular robot developed by Shimizu and Ishiguro<sup>1</sup>, on optimization of transportation of rail road grid [9], [10] and addressed the estimation of phase response curve in the oscillatory plasmodium by applying the theoretical method proposed by Ota et al. [11]<sup>2</sup>.

## X. SUMMARY AND FUTURE WORKS

We quantitatively analyzed the network morphology depending on environmental condition. We elucidate that the plasmodium shows hexagonal lattice under attractive condition. However the network under repulsive condition is not simple tree-graph network but with processes of generation/degeneration of edges. We are analyzing the process.

To achieve the goal mentioned in §II we quantified the network growth process and obtained some hint concerned in the rules. In respect to adaptation behavior of plasmodia, we could discuss some speculation; The most efficient morphology for the plasmodia in repulsive condition could be tree-graph to escape faster from bad environment to find better one with limited resources and low energy consumption by using generation/degeneration process; On the other hand, the most efficient morphology for the attractive condition could be dense network with hierarchal thin tubes to absorb much more nutrient. To discuss more quantitatively, we still have left several subjects to examine, e.g., how are the efficiencies of migration, nutrient absorption, transportation of protoplasm, finding probability of better environment, and etc.

<sup>1</sup>Collaboration with M. Shimizu and A. Ishiguro, Tohoku University

<sup>2</sup>Collaboration with K. Ota and T. Aoyagi, Kyoto University

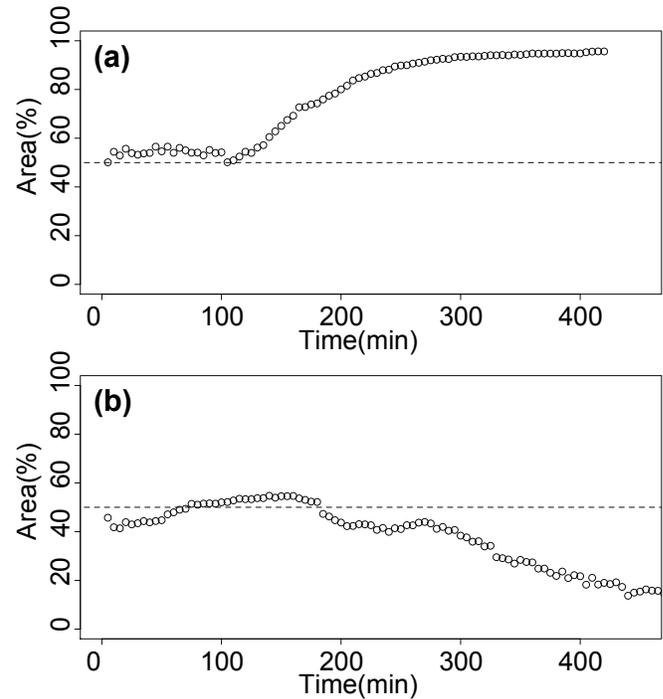


Fig. 6. Determination behavior placed at a boundary of two different conditions (a) Nutrient contained (up) vs harmful condition (down); 0.9 % agar with 1 w/v % oat extract and 0.3 % agar with 10 mM KCl. (b) Nutrient contained (up) vs hard substrate (down); 0.9 % agar with 1 w/v % oat extract and 1.5 % agar without chemicals.

## REFERENCES

- [1] Nelson, T. and Dengler N., Leaf cascular pattern formation. *The Plant Cell*, 9, 1121-1135 (1997).
- [2] Burton J. L., and Franks, N. R., The foraging ecology of the army ant *Ection rapax* An Ergonomic enigma? *Ecol. Entomol.* 10, 131-141 (1985)
- [3] Barthélemy, M. and Flammini A., Modeling urban street patterns. *Phys. Rev. Lett.*, 100, 138702 (2008).
- [4] Takamatsu, A., Takaba, E. and Takizawa, G., Environment-dependent morphology in plasmodium of true slime mold *Physarum polycephalum* and a network growth model. *J. theor. biol.*, 256, 29-44 (2009).
- [5] A. Takamatsu, R. Okamoto, M. Ito, and T. Gomi, (2009) "Adaptation by environment-dependent-dynamical network in *Physarum*", Proceedings of 3rd International Symposium on Mobiligence in Awaji, 357-360.
- [6] Newman M. E. J., *The Structure and Function of Complex Networks*, SIAM Review, 45, 167-256 (2003)
- [7] Buhl, J., Gautrais, J., Solé, R. V., Kuntz, P., Valverde, S., Deneubourg, J.L., Theraulaz, G. Efficiency and robustness in ant networks of galleries. *Eur. Phys. J. B* 42, 123-129 (2004).
- [8] Y. Kagawa and A. Takamatsu, "Synchronization and spatiotemporal patterns in coupled phase oscillators on a weighted planar network", *Phys. Rev. E*, Vol. 79, pp. 046216, 2009.
- [9] S. Watanabe, A. Tero, A. Takamatsu, T. Nakagaki, "Raid grid optimization by an algorithm inspired from *Physarum*", Proceedings of 3rd International Symposium on Mobiligence in Awaji, 399-402.
- [10] S. Watanabe, A. Tero, A. Takamatsu, T. Nakagaki, "Rail grid optimization by an algorithm biologically inspired from an amoeba-like organism of true slime mold", Proceedings of the 2009 International Symposium on Nonlinear Theory and its Applications, Hokkaido, 356-359.
- [11] K. Ota, M. Nomura, T. Aoyagi (2009) "Weighted dpike-triggered average of a fluctuating stimulus yielding the phase response curve", *Phys Rev. Lett* 103, 024101.

# Measurement and Modeling of Human Movement Mastery Process

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## I. INTRODUCTION

The aim of this research is to clarify the movement mastery process of humans. In particular, we focus on the human ability to reduce the total energy of human muscles in the process of master of skillful motions. In most of sports or skillful motions, relaxation of muscles is extremely important to generate high speed and precise motions. In order to clarify the mastery process, this research tries to make mathematical models of movement mastery process basing on measurement and observation of human skillful motions.

It seems that complex controllers are needed to control a muscular structure of humans. However, this research reveals that a simple controller such as linear transformation from sensors to actuators without using kinematics and dynamics is effective for skillful motions. The fact that linear transformation can generate precise motions with saving energy means that the proposed method effectively uses the characteristics of kinematics and dynamics of humans. Therefore, it is possible to consider that the proposed control method means “Implicit Control”[1].

Form the results of this research, it is shown that neither kinematics, inverse kinematics, dynamics, nor inverse dynamics is needed to control multi-joint structure such as humans and robots. An overview of this research is demonstrated by Fig.1.

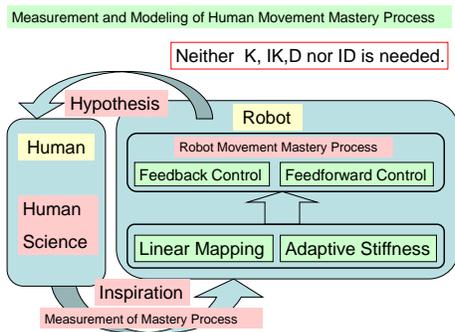


Fig.1 Realization of a movement mastery process model

## II. Measurement of Human Motion

This report focuses on planar movement of a human upper arm as shown in Fig.2. In order to give the subject’s hand an external force by an elastic force field and to measure the hand position of the subject, a robotic arm with two joints which

moves in a plane was developed. The height of the robot arm was adjusted in advance so that the subject can move his arm comfortably and smoothly. The subject grasps a grip attached to the endpoint of the robot arm. The external load generated by springs (Spring constant: 4.52N/mm) attached to the joints of the robot arm is given the subject’s hand. The endpoint

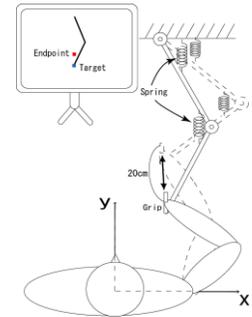


Fig.2 Experimental system

position of the subject is calculated from information of rotary encoders attached to the joints of the robot and kinematic information of the robot. The calculated end-position is illustrated, together with the target, on the display real-time. The subject endpoint on the display is colored with red if it is within a radius of 4[cm] from the target or with blue otherwise, and the subject can confirm the color real-time during movement. Further, we measured electromyography (EMG) signals of six muscles (Biceps brachii, Triceps brachii lateral head, Brachioradialis, Pectoralis major, Deltoideus posterior, and Deltoideus posterior), using the EMG device (ML880 PowerLab 16/30 (made by AD instruments), DL-141(made by S&ME)). The EMG signals were sampled at 4k Hz.

The subject was requested so as to accurately track the target point appearing on the display real-time which travels periodically at a distance of 0.2[m] and a speed of 2[s] per cycle. Each cycle was counted as a trial and the subject performed 196 trials totally. In the experiment, the subject had 7-8 breaks to avoid fatiguing.

The experimental results show that the integral EMG values concerning the biceps brachii, the triceps brachii lateral head, and the brachioradialis tend to increase as the trial increase. While, those concerning the deltoideus posterior tends to decrease. Totally, it was difficult to make a clear model of motion mastery process form the result of EMG. However, the subjects reported that they could relax the muscles which are not needed for making the motion as they master the motions.

## III. Motion Energy Saving by Adaptive Stiffness

### A. Simultaneous Control of Motion Pattern and Joint Stiffness

It seems that humans reduce the energy of the muscles by making good use of potential energy and joint stiffness. In other words, potential energy and energy supplied by muscles

are effectively compensated. In this study, we have discovered one property of the multi-joint structures which can generate periodic motions with minimum actuator torque by linear state feedback of angular velocity [2][3]. Based on this property, we propose a new controller that adaptively adjusts joint stiffness and motion patterns for biped locomotion. To generate motion patterns, a delay feedback method is utilized in this research.

## B. Problem Formulation

Here we consider a biped locomotion robot. When the robot swings a leg, dynamics is given by

$$\mathbf{R}(\mathbf{q})\ddot{\mathbf{q}} + \left\{ \frac{1}{2} \dot{\mathbf{R}}(\mathbf{q}) + \mathbf{S}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{D} \right\} \dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \mathbf{K}(\mathbf{q} - \mathbf{q}_e) = \boldsymbol{\tau}. \quad (1)$$

In this study, we try to minimize actuator torque while generating periodic motions. A cost function can be given by

$$J = b \int_0^T \boldsymbol{\tau}^T \mathbf{A}^{-1} \boldsymbol{\tau} dt. \quad (2)$$

## C. Optimal Actuator Torque

We have analytically derived that optimal actuator torque  $\boldsymbol{\tau}_{\text{opt}}$  can be described by linear state feedback of velocity  $\dot{\mathbf{q}}$  as follow:

$$\boldsymbol{\tau}_{\text{opt}} = \mathbf{A}\dot{\mathbf{q}}. \quad (3)$$

This relationship is clarified using energy-based analysis or the Hamilton-Jacobi equation. This result is the same as conventional resonance in the sense of generating periodic motions by linear velocity feedback with using minimum actuator torque. Therefore, our proposed concept can be regarded as a kind of extension of conventional resonance to multi-joint structures.

## D. Control Method

This study proposes the following control method.

$$\boldsymbol{\tau} = -\mathbf{K}_v(\dot{\mathbf{q}} - \dot{\mathbf{q}}_d) + \hat{b}\mathbf{A}\dot{\mathbf{q}} \quad (4)$$

$$\hat{b} = -\gamma_a \dot{\mathbf{q}}^T (\dot{\mathbf{q}} - \dot{\mathbf{q}}_d) \quad (5)$$

$$\dot{\mathbf{q}}_d(t) = (1 - \alpha)\dot{\mathbf{q}}_d(t - T) - \alpha\dot{\mathbf{q}}(t - T) \quad (6)$$

$$\dot{\mathbf{k}} = \Gamma\mathbf{Q}(\dot{\mathbf{q}} - \dot{\mathbf{q}}_d) \quad (7)$$

The term of  $-\mathbf{K}_v(\dot{\mathbf{q}} - \dot{\mathbf{q}}_d)$  in Eq.(4) means velocity error feedback. The desired motion is adjusted by Eq.(6). This structure is the same as delayed feedback control. It has been pointed out that delayed feedback control can realize convergence of state variables to unknown periodic equilibriums. When the motions will converge to the desired ones  $\dot{\mathbf{q}} \rightarrow \dot{\mathbf{q}}_d$ , the actuator torque will be the same as optimal actuator torque of Eq.(3). We also use adaptive parameter adjustment of Eq.(5) and Eq.(7). We have proved that the structure of the Eq.(7) can optimize joint stiffness.

## E. Simulation

We conducted a numerical simulation to verify the effectiveness of the proposed controller. We used the walking model as shown in the Fig.3.

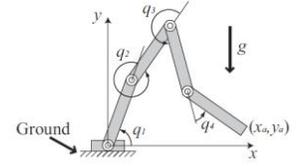


Fig. 3 Simulation Model

Simulation results showed that the proposed controller could generate periodic motion and the actuator torque converged to the optimal condition of Eq.(3). Therefore, it has been verified that the proposed controller can generate periodic motions that require minimum actuator torque.

## IV. Motion Control based on Linear Transformation for an Arm Model with 2-DOF and 6-Muscles

### A. Outline

An arm model with 2-DOF and 6-muscles shown in Fig.4 is investigated. It is important to consider how humans control the muscles basing on the data from the vision. Here, to simplify this problem, it is assumed that there is no time delay from the vision to the muscles. A final goal is to make a simple model which can explain the process of master of human skillful motions for the muscular structure with redundant actuation as seen in Fig.4.

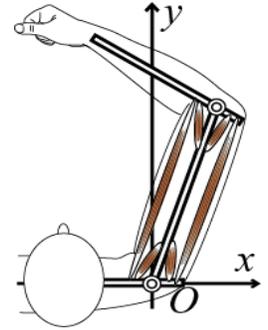


Fig.4 Arm Model with 2DOF and 6 muscles

### B. Linearity Evaluation of Mapping from Hand Coordinates to Muscle Length and Diagonalization by Two-joint Muscles

The mapping from visual information to motor command is an important issue in the study of voluntary arm movement. Planning of reaching movement to a visual target is generally based on the inverse kinematics, which is the mapping from the hand position in Cartesian coordinates to the joint angles of the arm. This mapping is nonlinear.

On the other hand, it is reported that the mapping from the hand position described in binocular visual coordinates to the joint angles of the arm is approximated by a linear function [5]. The linear mapping simplifies the control system.

This study examined the linearity of the mapping from the hand position to the muscle length. Binocular visual space is defined as the vergence angle and the horizontal direction. The kinematic model of the arm consists of two links and two joints. The elbow joint and the shoulder joint have 1 DOF and the arm moves on the horizontal plane.

The muscle lengths were determined by the use of the following three models.

Model 1: Pulley model (Fig.5(a))

The moment arms are constant. This model is used frequently in many papers.

Model 2: A model where muscles are fixed on the links directly.(Fig.4)

Model 3. An anatomical model proposed by Pigeon[5]

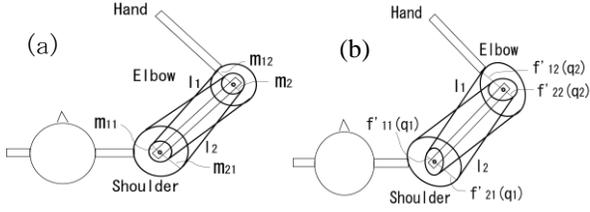


Fig.5 musculo-skeletal models

The length of mono-articular muscle determined in model 1 is proportional to the joint angle, thus the muscle length is proportional to the hand position in binocular visual coordinates. The length of mono-articular muscle determined in model 2 and model 3 are nearly proportional to the joint angles except the singular posture. Moreover the muscle length of biceps brachii is proportional to the distance of hand position from the head. If the model shown in Fig.5(b), we can improve the approximate accuracy in the linearization. These results imply the linear approximation of musculoskeletal model of human being on task oriented coordinates. Applying the linear model in three dimensional coordinates is a future subject.

### C. Feedback Control based on Linear Transformation

On the arm model shown in Fig.4, the relation between the joint torque  $\tau$  (2x1) and the muscle tension  $\alpha$  (6x1) is given by

$$\tau = \mathbf{W}(\mathbf{q}) \alpha \quad (8)$$

where  $\mathbf{W}(\mathbf{q})$ : a matrix (2x6) and  $\mathbf{q}$  (2x1): a joint angle coordinates vector. The details of  $\mathbf{W}(\mathbf{q})$  are shown in [8].

Here, we propose a robust sensory feedback motion control scheme given by

$$\alpha = \mathbf{M} [\mathbf{K}_p (\mathbf{x}_d - \mathbf{x}) - \mathbf{K}_v \dot{\mathbf{x}}] \quad (9)$$

where  $\mathbf{M}$ : appropriate matrix (6x2),  $\mathbf{K}_p$ : position feedback gain matrix (2x2),  $\mathbf{K}_v$ : velocity feedback gain matrix (2x2),  $\mathbf{x}(t)$ : position vector in the task-oriented coordinates (2x1),  $\mathbf{x}_d$ : desired position vector in the task-oriented coordinates (2x1), and  $\dot{\mathbf{x}}$ : velocity vector. Here, we do not consider gravity to simplify the problem.

If the kinematics parameters are exactly given, the matrix  $\mathbf{M}$  is easily set

$$\mathbf{M} = \mathbf{W}^+ \mathbf{J}^T \quad (10)$$

where  $\mathbf{W}^+ = \mathbf{W}^T (\mathbf{W} \mathbf{W}^T)^{-1}$ : pseudo-inverse matrix (6x2) and  $\mathbf{J}$ : Jacobian matrix from joint angle coordinates to task oriented coordinates (2x2). As the results, the stability to the desired point  $\mathbf{x}_d$  can be guaranteed as seen in [6]. However, it will be occurred that the sensor coordinates or the force directions contains the parameter errors. Therefore, the robustness on the parameter error is crucially important in making a model of human motor control. In this research, the

condition on the robustness has been obtained as follows:

$$\mathbf{W} \mathbf{M} \mathbf{J} > \mathbf{0}. \quad (11)$$

The details of stability proof are shown in [8]. From some simulation results, we have already confirmed that a matrix  $\mathbf{M}$  whose all elements are constant can make stable motions. In this simulation, the matrix  $\mathbf{M}$  is set

$$\mathbf{M} = \begin{bmatrix} -1 & 1 & 0 & 0 & -1 & 1 \\ 0 & 0 & -1 & 1 & -1 & 1 \end{bmatrix}^T. \quad (12)$$

The motion converges to the desired point and appropriate internal forces among muscles are generated. In this simulation, the muscle force is set zero if the value of the muscle force calculated by Eq.(9) is negative. The motion stability was proven by using a Liapunov function and geometric condition, PD feedback gain ratio condition, and gain condition were made clear. The details are shown in [8].

It is possible to control the arm model with keeping that each muscle force  $\alpha$  is positive. For this, the following PID controller is used.

$$\alpha = \mathbf{M} \left[ K_p (x_d - x) - K_v \dot{x} + \int_0^t K_i (x_d - x) d\sigma \right] + \alpha_0 \quad (13)$$

$$\alpha_0 = [60 \ 60 \ 60 \ 60 \ 60 \ 60]^T$$

It should be noted that the vector  $\alpha_0$  which mainly make the internal forces among muscles can be easily set as a constant vector.

### D. Feedforward Control based on Linear Transformation

Here, a desired motion is given by a time trajectory. To precisely realize the desired motion, ILC(Iterative Learning Control) is utilized. The ILC for the arm model is represented by

$$\alpha_k = \mathbf{M} [K_p (x_d - x) - K_v (\dot{x}_d - \dot{x})] + \alpha_{fk} + \theta \alpha_0$$

$$\alpha_{fk} = \mathbf{M} f_k$$

$$f_{k+1} = f_k + \Phi(\dot{x}_d - \dot{x}) \quad (14)$$

$$\text{where } \theta = 60, \quad \alpha_0 = [1, 1, 1, 1, 1, 1]^T$$

The simulation results given by ILC is demonstrated in Fig.6.

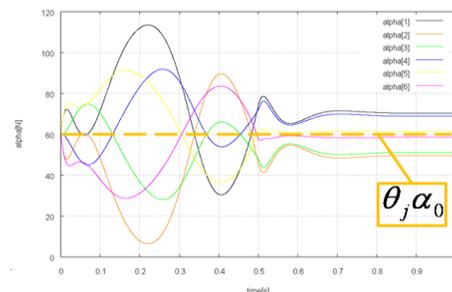


Fig.6 Simulation results of each muscular force

This case also used the constant matrix given by Eq.(12). It is important that neither dynamics nor kinematic is utilized for ILC.

#### E. Movement Mastery Model for Reduction of Internal Muscle Force

In the case of Fig.6, each muscular force  $\alpha$  can become positive because  $\theta$  is sufficiently large. It means that antagonistic muscular tense each other or the internal forces become large. In other words, it is similar to the situation that humans tense muscles before mastering the desired motions.

Here, we propose a movement mastery model to reduce the internal forces among muscles. The proposed model is represented by

$$\begin{aligned}\alpha_{kj} &= M[K_p(x_d - x) - K_v(\dot{x}_d - \dot{x})] + \alpha_{fkj} + \theta_j \alpha_0 \\ \alpha_{fkj} &= Mf_k \\ f_{k+1} &= f_k + \Phi(\dot{x}_d - \dot{x}) \\ \theta_{j+1} &= \lambda \theta_j \quad 0 < \lambda < 1\end{aligned}\tag{15}$$

In this model, the parts of each muscular force  $\alpha$  which are smaller than  $\theta$  ( $\theta = 60$  in Fig.6) are omitted for making next another learning process. The symbol  $j$  stands for the another iteration. For  $j=2$ , a constant  $\lambda$  ( $0 < \lambda < 1$ ) is multiplied by  $\theta_j$ . Next,  $\theta_2$  is used for learning iteration for  $k$ . It works for reducing the internal forces. In this simulation, we set  $\lambda = 0.9$  and Fig.7 demonstrates the results of internal force reduction with keeping positive muscular forces. In Fig.7, we set  $k=15$ ,  $j=13$ .

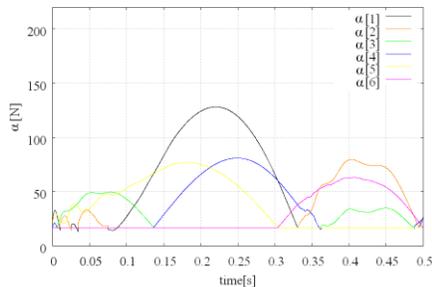


Fig.7 Simulation result of internal force reduction

## V. CONCLUSION

This research proposed models of movement mastery process. In the proposed models, stiffness adaptation for energy saving and learning for internal force reduction were proposed. If the internal forces are large, joint stiffness becomes large because of elasticity of muscles. Therefore, it is interesting to consider the relation between internal forces and joint stiffness. It is a future work of this research.

It is expected that the movement mastery model obtained

in this research is used for human motion science as seen in Fig.1. Moreover, the result of linear transformation from vision to motion is useful for realization of new robots. For example, if we use linear transformation for visual feedback system, encoders of robots are not needed [9]. This result will be important in the case that a robot must be made by minimum number of elements or cannot have joint angle sensors.

## REFERENCES

- [1] Koichi Osuka Akio Ishiguro, Xin-Zhi Zheng, Yasuhiro Sugimoto, Dai Owaki "Implicit Control Law: A Common Principle of Mobiligence" Proceedings of the 3<sup>rd</sup> Interantional Symposium on Mobiligence in Awaji, November 19-21, 2009
- [2] M. Uemura, K. Kanaoka, S. Kawamura, "A New Control Method Utilizing Stiffness Adjustment of Mechanical Elastic Elements for Serial Link Systems", IEEE International Conference on Robotics and Automation 2007, pp.1437-1442, 2007.
- [3] M.Uemura and S.Kawamura "Resonance-based Motion Control Method for Multi Joint Robot through Combination Stiffness Adaptation and Iterative Learning Control" Proc. of the 2009 International Conference on Robotics and Automation (ICRA2009) pp.1543-1548
- [4] M.Uemura, K.Kimukra and S.Kawamura "Generation of Energy Saving Motion for Biped Walking Robot through Resonance-based Control Method" Proc. of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2009) pp.2928-2933
- [5] T.Mitsuda et al. "Binocular visual servoing based on linear time-invariant mapping", Advanved Robotics, Vol.11, No.5, pp.429-443, 1997
- [6] Pascale Pigeon, L'Hocine Yahia and Anatol G. Feldman, "Moment arms and lengths of human upper limb muscle as functions of joint angles", J.Biomechanics, Vol.29, No.10, pp.1365-1370, 1996
- [7] Kenji Tahara and Zhi-Wei Luo, "On Dynamic Control Meahcnisms of Redundant Human Musculo-Skeletal System" pp.217-247 Advances in Robot Control, Springer 2006 (Editor S. Kawamura and M. Svinin)
- [8] Sadao Kawamura, Yuuji Hayashi, Takashi Mitsuda, Mitsunori Uemura, Masahiro Sekimoto, and Tadao Isaka "Stability Conditions of Feedback Robot Motion Control Based on Linear Transformation from Vision to Motion" Proceedings. of the 3<sup>rd</sup> Interantional Symposium on Mobiligence in Awaji, November 19-21, 2009
- [9] Sadao Kawamura, Yuuji Hayashi, Takashi Mitsuda, Mitsunori Uemura, Masahiro Sekimoto "Stability Conditions of Feedback Motion Control based on Linear Transformation from Vision to Motion-Don't Robots Need Encoders?-" Proc. of the RSJ2009, 2009

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D01-16	Tadao Isaka	Ritsumeikan University	■
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# Publications, Awards, Patents

## Publications

### ● 2005

- Naohiro Saito, Hajime Mushiake, Kazuhiro Sakamoto, Yasuto Itoyama, Jun Tanji, Representation of Immediate and Final Behavioral Goals in the Monkey Prefrontal Cortex during an Instructed Delay Period, *Cerebral Cortex*, 15, 10, 1535-1546, 2005
- Yoshinari Makino, Masafumi Yano, Pictorial Cues Constrain Depth in da Vinci Stereopsis, *Vision Research*, 46, 1-2, 91-105, 2006
- Toshiyuki Kondo, Koji Ito, Periodic Motion Control by Modulating CPG Parameters based on Time-Series Recognition, Lecture Notes in Artificial Intelligence, 3630 (Proceedings of 8th European Conference, ECAL2005), 3630, 1, 906-915, 2005
- Masahiko Inase, Bao-Ming Li, Ichiro Takahashi, Toshio Iijima, Cue Familiarity Is Represented in Monkey Medial Prefrontal Cortex during Visuomotor Association Learning, *Experimental Brain Research*, 168, 1-2, 281-286, 2006
- Oshio Kenichi, Atsushi Chiba, Masahiko Inase, Delay Period Activity of Monkey Prefrontal Neurons during Duration-Discrimination Task, *European Journal of Neuroscience*, 2006
- Hirohumi Harada, Kaoru Takakusaki, Shinichi Kita, Mitsuyoshi Matsuda, Satoshi Nonaka, Takashi Sakamoto, Effects of Injecting GABAergic Agents into the Medullary Reticular Formation upon Swallowing Induced by the Superior Laryngeal Nerve Stimulation in Decerebrate Cats, *Neuroscience Research*, 51, 395-404, 2005
- Hiroto Yamada, Nobuhiko Takahashi, Satoshi Tanno, Miho Nagamine, Kaoru Takakusaki, Toshikatsu Okumura, A Selective Orexin-1 Receptor Antagonist, SB334867, blocks 2-DG-Induced Gastric Acid Secretion in Rats, *Neuroscience Letters*, 376, 2, 137-142, 2005
- Kaoru Takakusaki, Kazumi Takahashi, Kazuya Saitoh, Hirofumi Harada, Toshikatsu Okumura, Yukihiko Kayama, Yoshimasa Koyama, Orexinergic Projections to the Midbrain Mediate Alteration of Emotional Behavioral States from Locomotion to Cataplexy, *Journal of Physiology*, 568, 3, 1003-1020, 2005
- Kaoru Takakusaki, Kazuya Saitoh, Satoshi Nonaka, Toshikatsu Okumura, Naoyuki Miyokawa, Yoshimasa Koyama, Neurobiological Basis of State-Dependent Control of Motor Behaviors, Sleep and Biological Rhythms, 2006
- Futoshi Mori, Katsumi Nakajima, Shigemori Mori, Cortical and subcortical neural mechanisms for controlling bipedal gait in humans and Japanese macaques, *Human Movement Science*, in press
- Taizo Nakazato, Striatal Dopamine Release in the Rat during a Cued Lever-press Task for Food Reward and the Development of Changes over Time Measured Using High-speed Voltammetry, *Experimental Brain Research*, 166, 1, 137-146, 2005
- Shigeru Kitazawa, Kenji Kansaku, Sex difference in language lateralization may be task-dependent, *Brain*, 128, 5, E30, 2005
- Shinya Yamamoto, Shunjiro Moizumi, Shigeru Kitazawa, Referral of tactile sensation to the tips of L-shaped sticks, *Journal of Neurophysiology*, 93, 5, 2856-2863, 2005
- Kenji Kansaku, Shigeru Muraki, Shinji Uneyama, Yasunori Nishimori, Tomoyuki Kochiyama, Shigeru Yamane, Shigeru Kitazawa, Cortical activity in multiple motor areas during sequential finger movements: an application of independent component analysis, *NeuroImage*, 28, 3, 669-681, 2005
- Shigeru Kitazawa, Daniel M Wolpert, Rhythmicity, randomness and synchrony in climbing fiber signals, *Trends in Neurosciences*, 28, 11, 611-619, 2005
- Shigeru Kitazawa, Daniel M Wolpert, Response to Gilbert: Rhythmicity, randomness and synchrony in climbing fiber signals, *Trends in Neurosciences*, 29, 2, 66-67, 2006
- Sho Kakizawa, Taisuke Miyazaki, Dai Yanagihara, Masamitsu Iino, Masahiko Watanabe, Masanobu Kano, Maintenance of Presynaptic Function by AMPA Receptor-Mediated Excitatory Postsynaptic Activity in Adult Brain, *Proceedings of the National Academy of Sciences of the United States of America*, 102, 52, 19180-19185, 2005
- Yukihiko Takayasu, Masae Iino, Wataru Kagegawa, Hiroshi Maeno, Kei Watae, Keiji Wada, Dai Yanagihara, Taisuke Miyazaki, Okiru Komine, Masahiko Watanabe, Koichi Tanaka, Seiji Ozawa, Differential Roles of Glial and Neuronal Glutamate Transporters in Purkinje Cell Synapses, *Journal of Neuroscience*, 25, 38, 8788-8793, 2005
- Shinya Aoi, Kazuo Tsuchiya, Locomotion Control of a Biped Robot Using Nonlinear Oscillators, *Autonomous Robots*, 19, 3, 219-232, 2005
- Shinya Aoi, Kazuo Tsuchiya, Bifurcation and Chaos of a Simple Walking Model Driven by a Rhythmic Signal, *International Journal of Non-Linear Mechanics*, 41, 4, 438-446, 2006
- Shinya Aoi, Kazuo Tsuchiya, Self-stability of a Simple Walking Model Driven by a Rhythmic Signal, *Nonlinear Dynamics*, in press
- Shinya Aoi, Kazuo Tsuchiya, Stability Analysis of a Simple Walking Model Driven by an Oscillator with a Phase Reset Using Sensory Feedback, *IEEE Transactions on Robotics*, in press
- Katsuyoshi Tsujita, Hiroomi Toui, Kazuo Tsuchiya, Dynamic Turning Control of a Quadruped Locomotion Robot using Oscillators, *Advanced Robotics*, 19, 10, 1115-1133, 2005
- Masato Nakatsukasa, Eishi Hirasaki, Naomichi Ogihara, Energy expenditure of bipedal walking is higher than that of quadrupedal walking in Japanese macaques, *American Journal of Physical Anthropology*, in press
- Y. Matsumoto, S. Uroki, H. Aonuma and M. Mizunami, Nitric oxide-cGMP signaling is critical for cAMP-dependent long-term memory formation, *Learning & Memory*, 13, 1, 35-44, 2006
- Jun Ota, Multi-agent Robot Systems as Distributed Autonomous Systems, *Advanced Engineering Informatics*, 20, 1, 59-70, 2006
- Hiroshi Kimura, Kazuo Tsuchiya, Akio Ishiguro, Hartmut Witte (Eds.), *Adaptive Motion of Animals and Machines*, Springer (2006), 2006
- Taizo Nakazato, Maki Kagohashi, Kenji Yoshimi, Influence of pH on Voltammetric Measurement of Dopamine-, Biogenic Amines, 2006
- Taizo Nakazato, L-DOPA Itself Causes Increased Activity in Rats: The Clinical Implications, The Probable Roles of Dopamine as a Neurotransmitter, Eds: Misu Y and Goshima Y, CRC Press, NY, 229-241, 2005
- K. Niwa, J. Sakai, T. Karino, H. Aonuma, T. Watanabe, T. Ohyama, O. Inanami and M. Kuwabara, Reactive oxygen species mediate shear stress-induced fluid-phase endocytosis in vascular endothelial cells, *Free Radical Research*, 40, 2, 167-174, 2006
- J. Nagamoto, H. Aonuma and M. Hisada, Discrimination of conspecific individuals via cuticular pheromones by males of the cricket *Gryllus bimaculatus*, *Zool. Sci.*, 22, 1, 1079-1088, 2005
- Kanzaki R, Nagasawa S and Shimoyama I, Neural basis of odor-source searching behavior in insect brain systems evaluated with a mobile robot, *Chem. Senses*, 30, suppl 1, 285-286, 2005
- Wada S and Kanzaki R, Neural control mechanisms of the pheromone-triggered programmed behavior in male silkworms revealed by double-labeling of descending interneurons and the motor neuron, *J Comp Neurol*, 484, 1, 168-182, 2005
- Iwano M and Kanzaki R, Immunocytochemical Identification of Neuroactive Substances in the Antennal Lobe of the Male Silkworm *Moth Bombyx mori*, *Zool Sci*, 22, 1, 199-211, 2005
- Naraki S, Kawaza T and Kanzaki R, Basic characteristics of neuron network components in the antennal lobe of the silkworm, *Chem Senses*, 30, 1, A149-A150, 2005
- Yamasaki T, Isokawa T, Matsui M, Ikeno H and Kanzaki R, Reconstruction and simulation for three-dimensional morphological structure of insect neurons, *Neurocomputing*, 2006
- Yoshinari Makino, Hisanori Makino, Tsukasa Obara, Masafumi Yano, Brain Regions Related to Odor Learning and Memory in Terrestrial Slug, *Incarialia Frustrorferi*: Two Lobes of the Cerebral Ganglion Show Different Spatiotemporal Activities, *Proceedings of the 11th International Symposium on Artificial Life and Robotics*, OIST-1, 2006
- Ikuo Matsuo, and Masafumi Yano, A Computational Model of Echolocation: Restoration of an Acoustic Image from a Single-Emission Echo, *The Journal of the Acoustical Society of America* (149th Meeting of the Acoustical Society of America), 117, 4, 2553, 2005
- Masashi Ito, Masafumi Yano, A Local Vector Coding for High Quality Voice Analysis/Synthesis, *The Journal of the Acoustical Society of America* (150th Meeting of the Acoustical Society of America), 118, 3, 2024, 2005
- Koji Ito, Takeshi Sakurada, Makoto Doi, Toshiyuki Kondo, Impedance Adaptation of Arm Movements under Dynamic Environments, *Proceeding of SICE Annual Conference 2005*, WP1-03-02, 1, 3305-3310, 2005
- Koji Ito, Takahiro Shoyama, Toshiyuki Kondo, Lower-limb Joint Torque and Position Controls by Functional Electrical Stimulation (FES), *Proceeding of Complex Medical Engineering (CME2005)*, 559-564, 2005
- Tomzaki Nagano, Toshiyuki Kondo, Koji Ito, Motion Pattern Generation for Multi-link System based on Distributed Kinematics and Dynamics with Time Delay, *Proceedings of SICE Annual Conference 2005*, MA2-01-6, 2005
- Akira Mura, Masahiko Inase, Self Generated Action Monitoring by Mirror Neurons in the Inferior Parietal Cortex, *Proceedings of Vision Science Society 5th Annual Meeting, Satellite Workshop, From Eye to Hand: The Role of Vision in Grasping*, 2005
- Atsushi Chiba, Kenichi Oshio, Masahiko Inase, Neuronal Activity in the Monkey Striatum during a Duration Discrimination Task, *Proceedings of Neuroscience 2005, 35th Annual Meeting of Society for Neuroscience*, 4135, 2005
- Kaoru Takakusaki, The Control of Basal Ganglia on Postural Muscle Tone And Locomotion, *35th International Union of Physiological Science*, 2005
- Kaoru Takakusaki, Kazuya Saitoh, A New Category of Spinal Interneurons That Mediate Atonia in Cats, *Proceedings of Neuroscience 2005, 35th Annual Meeting of Society for Neuroscience*, 863.17, 2005
- Hirohumi Harada, Kaoru Takakusaki, Yoshio Bando, Satoshi Nonaka, GABAergic Control of Swallowing in Cats, *Proceedings of Neuroscience 2005, 35th Annual Meeting of Society for Neuroscience*, 573.24, 2005
- Futoshi Mori, Katsumi Nakajima, Hideo Tsukada, Shigemori Mori, Primary, supplementary and premotor cortices are involved in the execution and control of operant-trained bipedal treadmill walking in Japanese monkey, *Proceedings of the 2006 International Congress on Gait & Mental Function*, 2006
- Naomi Wada, Futoshi Mori, Norihiro Kato, Shinji Hirano, Wakana Iwamoto, Go Suzuki, Shigemori Mori, Kinematic and electromyographic studies on rat bipedal-walking model, *International Society for Postural and Gait Research XVIIIth Conference*, 2006
- Norihiro Kato, Shinji Hirano, Wakana Iwamoto, Go Suzuki, Futoshi Mori, Naomi Wada, Shigemori Mori, Influence of bipedal walking on neural systems: spiral reflexes in the lumbar spinal cords in rat bipedal walking models, *International Society for Postural and Gait Research XVIIIth Conference*, 2006
- Kenji Yoshimi, Taizo Nakazato, Kazuo Tsuchiya, Seichiro Shimizu, Akira Komatsu, Nobutaka Hattori, Yoshikuni Mizuno, Voltammetric Measurement of Striatal Extracellular Dopamine Changes Induced by Physiological Stimuli and Trace Amine Mimetics, 2005
- Maki Kagohashi, Taizo Nakazato, Shigeru Kitazawa, Yoshikuni Mizuno, Dopamine Release in the Rat Striatum during the Cued Lever-press Task and the Effect of Serotonin Neuron on Its Release, 2005
- Shigeru Kitazawa, Where tactile stimuli are ordered in time, *Neuroscience Seminar Series 2005, 2005*
- Shigeru Kitazawa, Frames of reference for tactile perception, *Cognition and Action, JSPS-UCL symposium*, 2005
- Shigeru Kitazawa, Where tactile signals are ordered in time, *ESF-EMBO Symposium on Three-Dimensional Sensory and Motor Space: Probabilistic Mechanisms of Learning and Development in Sensorimotor Systems*, 2005
- Shigeru Kitazawa, Inferring the level of language comprehension during story listening, *Neuroethics of Nurturing the Brain, Annual Meeting 2005, Japanese Society for Neuroscience*, 2005
- Shinya Aoi, Kazuo Tsuchiya, Transition from Quadrupedal to Bipedal Locomotion, *Proceedings of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Edmonton, Canada (IROS2005), 3419-3424, 2005
- Shinya Aoi, Kazuo Tsuchiya, Turning of a Biped Robot Driven by Nonlinear Oscillators, *Proceedings of the 3rd International Symposium on Adaptive Motion of Animals and Machines*, Illmenau, Germany (AMAM2005), 2005
- Shinya Aoi, Kazuo Tsuchiya, Feedback Control of a Simple Walking Model Driven by an Oscillator, *Proceedings of the 2004 IEEE International Conference on Robotics and Automation*, Orlando, FL (ICRA2004), accepted
- Katsuyoshi Tsujita, Manabu Kawakami, Kazuo Tsuchiya, Optimal Gait Pattern of a Quadruped Locomotion Robot, *Proceedings of the 3rd International Symposium on Adaptive Motion of Animals and Machines*, Illmenau, Germany (AMAM2005), 2005
- Naomichi Ogihara, Eishi Hirasaki, Masato Nakatsukasa, Energy efficient bipedal locomotor strategy in bipedally-trained Japanese macaques, *Proceedings of the 3rd International Symposium on Adaptive Motion of Animals and Machines*, Illmenau, Germany (AMAM2005), 2005
- Takeshi Takuma, Koh Hosoda, Minoru Asada, Stabilization of Biped with Pneumatic Actuators against Terrain Changes, *Proceedings of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, (IROS2005), 2775-2780, 2005
- Koh Hosoda, Takeshi Takuma, Ballistic Control for 2D/3D Pneumatic Actuated Walking Robots, *Proceedings of 3rd International Symposium on Adaptive Motion in Animals and Machines*, 2005
- H. Kimura, Y. Fukuroka, H. Katayuki, Mechanical Design of a Quadruped Tekken3 & 4 and Navigation System Using Laser Range Sensor, *Proceedings of International Symposium on Robotics (ISR2005)*, 2005
- Z.G Zhang, Y. Fukuroka and H. Kimura, Adaptive Running of a Quadruped Robot Using Delayed Feedback Control, *Proceedings of IEEE Robotics and Automation (ICRA2005)*, 3750-3755, 2005
- K. Inoue, S. Ma, C. Jin, Optimization of CPG-Network for Decentralized Control of a Snake-Like Robot, *IEEE International Conference on Robotics and Biomimetics (ROBIO2005)*, 730-735, 2005
- T. Fujiki, K. Kawahata, H. Asama, Adaptive Action Selection of Body Expansion Behavior in Multi-Robot System using Communication, *Intelligent Autonomous Systems 9*, 632-639, 2006
- Chomchana Trewai, Jun Ota and Tamio Arai, Self-organizing Planner for Multiple Mobile Robot Exploration and Patrol, *Intelligent Autonomous Systems 9*, 622-631, 2006
- Masao Sugi, Yusuke Tamura, Makoto Nakaïdo, Jun Ota, Tamio Arai et al., Human Supporting Production Cell Attentive Workbench, *Intelligent Autonomous Systems 9*, 740-747, 2006
- Tetsuro Furuta, Daisuke Kurabayashi, Masahito Nara, Control of a Nonlinear Oscillator Network via Structural Transition, *Distributed Autonomous Robotic Systems*, 7, 2006
- Gou Nishida, Masaki Yamakita, Formal Distributed Port-Hamiltonian Representation of Field Equation, *Proceedings of the 2005 IEEE International Conference on Decision and Control*, 12-25, 2005
- Akio Ishiguro, Hiroaki Matsuba, Tomoki Maegawa, Masahiro Shimizu, A Modular Robot That Self-Assembles, *Proceedings of the 9th International Conference on Intelligent Autonomous Systems (IAS-9)*, 585-594, 2006
- Kazuhiro Sakamoto, Toru Orizawa, Masafumi Yano, Competition Between Spatial and Temporal Factors in Simple Apparent Motion is Modulated by Laterality, *Proceedings of the 4th IEEE International Conference on Development and Learning (ICDL-05)*, 175-179, 2005
- Kazuhiro Sakamoto, Hajime Mushiake, Naohiro Saito, Jun Tanji, Transient Synchrony and Dynamical Representation of Behavioral Goals of the Prefrontal Cortex, *Proceedings of the 4th IEEE International Conference on Development and Learning (ICDL-05)*, 207-211, 2005
- D. Hatakeyama, E. Ito, H. Aonuma and K. Elekes, Distribution of glutamate-like immunoreactive neurons in the adult and developing nervous system of gastropod molluscs (*Lymnaea stagnalis* L.), *Clin Neurosci*, 58, S1, 39, 2005
- Yasuhiro Sugimoto, Koichi Osuka, Stability Analysis of Passive-Dynamic-Walking focusing on the Inner Structure of Poincare Map, *Proc. of 12th International Conference on Advanced Robotics (ICAR 2005)*, 2005
- Yasuhiro Sugimoto, Koichi Osuka, Stability Analysis and Walking Control of Passive-Dynamic-Walking with an approximate analytical Poincare map, *Proc. of IROS Workshop on Morphology, Control and Passive Dynamics*, 2005
- Koichi Osuka, Yasuhiro Sugimoto, A Stability Principle of Passive Dynamic Walk-Feedback Structure Embedded in the Poincare Map-, *Proceedings of the 3rd International Symposium on Adaptive Motion of Animals and Machines*, Illmenau, Germany (AMAM2005), 2005
- H. Kimura, Y. Fukuroka and T. Minura, Dynamics Based Integration of Motion Adaptation for a Quadruped Robot, *Adaptive Motion of Animals and Machines*, 215-224, 2005
- Futoshi Mori, Katsumi Nakajima, Shigemori Mori, Control of bipedal walking in the Japanese monkey, *M. fasciata*: Reactive and anticipatory control mechanisms, *Adaptive Motion of Animals and Machines*, 249-259, 2005
- Shigemori Mori, Futoshi Mori, Katsumi Nakajima, Higher nervous control of quadrupedal vs bipedal locomotion in non-human primates: Common and specific properties, *Adaptive Motion of Animals and Machines*, 53-65, 2006
- Naomichi Ogihara, Nobutoshi Yamazaki, Computer simulation of bipedal locomotion: Toward elucidating correlations among musculoskeletal morphology, energetics, and the origin of bipedalism, *Iskida, H, Tuttle, R, Pickford, M, Ogihara, N, Nakatsukasa, M (eds), Human Origins and Environmental Backgrounds*, Springer, New York, 167-174, 2006
- Masato Nakatsukasa, Eishi Hirasaki, Naomichi Ogihara, Locomotor energetics in nonhuman primates: A review of recent studies on bipedal performing macaques, *Iskida, H, Tuttle, R, Pickford, M, Ogihara, N, Nakatsukasa, M (eds), Human Origins and Environmental Backgrounds*, Springer, New York, 157-166, 2006

84. Eishi Hirasaki, Naomichi Ogihara, Masato Nakatsukasa, Primates trained for bipedal locomotion as a model for studying the evolution of bipedal locomotion, Ishida, H., Tuttle, R., Pickford, M., Ogihara, N., Nakatsukasa, M. (eds), *Human Origins and Environmental Backgrounds*, Springer, New York, 149-155, 2006
85. Kaoru Takakusaki, Kazuya Saitoh, Makoto Kashiwayanagi, The Pedunculopontine Nucleus and the Basal Ganglia in Locomotion, Recent Breakthroughs in Basal Ganglia Research, (ed by E. Bezard), 2006
86. Kazuhiro Sakamoto, Hajime Mushiaki, Naohiro Saito, Jun Tanji, Neuronal Synchrony and Representation of Behavioral Goals in the Prefrontal Cortex of the Monkey during a Path-Planning Task, *Neuroscience Research*, 52, suppl., s148, 2005
87. Yoshinari Makino, Masafumi Yano, Pictorial Depth Cues Constrain Stereoscopic Depth in da Vinci Stereopsis, *Neuroscience Research*, 52, suppl., s104, 2005
88. Kaoru Takakusaki, Spiral Striatum Mediating Muscular Atonia in Cats, Proceedings of the 82nd Annual Meeting, 55, Suppl, S182, 2005
89. Kaoru Takakusaki, Basal Ganglia Control Brain Function, Abstracts of the 28th Annual Meeting of the Japanese Neuroscience Society, *Neuroscience Research*, 52, Suppl, S32, 2005
90. Yoshio Bando, Kaoru Takakusaki, Ryouji Terayama, Shigetaka Yoshida, Conduction Properties of Corpus Callosum in Mice in Vivo, Abstracts of the 28th Annual Meeting of the Japanese Neuroscience Society, *Neuroscience Research*, 52, Suppl, S67, 2005
91. Maki Kagohashi, Taizo Nakazato, Shigeru Kitazawa, Yoshikuni Mizuno, Development of Wireless Voltammetry for Measuring Dopamine and Serotonin., *Neuroscience Research*, S221, 2005
- 2006
92. Yoshinari Makino, Masafumi Yano, Pictorial Cues Constrain Depth in da Vinci Stereopsis, *Vision Research* 46,1-291-105,2006
93. Naohiro Saito, Hajime Mushiaki, Kazuhiro Sakamoto, Yasuto Itoyama, Jun Tanji, Representation of Immediate and Final Behavioral Goals in the Monkey Prefrontal Cortex during an Instructed Delay Period, *Cerebral Cortex*, 15,10,1535 - 1546,2005
94. Kazuhiro SAKAMOTO, Takayuki SUGIURA, Toshihiko KAKU, Toru ONIZAWA and Masafumi YANO, Spatiotemporal balance in competing apparent motion is not predicted from the strength of the single-motion percept, *Perception*, 35, 947-957, 2006
95. Hajime Mushiaki, Naohiro Saito, Kazuhiro Sakamoto, Yasuto Itoyama, and Jun Tanji, Activity in the Lateral Prefrontal Cortex Reflects Multiple Steps of Future Events in Action Plans, *Neuron*, 50, 631-641, 2006
96. Yoshinari Makino, Hisanori Makinae, Tsukasa Obara, Haruki Miura and Masafumi Yano, Observations of Olfactory Information Flows within Brain of the Terrestrial Slug, *Incalia frutstorferi*, Proceeding of 2006 International Joint Conference on Neural Networks, 7605-7612, 2006
97. Masashi Ito, Masafumi Yano, High-quality voice modification based on Local Vector Coding, Proceeding of AES Japan Conference, P-17,
98. Takuhiro Watanabe, Keita Motonami, Kazuhiro Sakamoto, Jun Deguchi, Risato Kobayashi, Ken Komiya, Keiji Okumura, Takafumi Fukushima, Hiroyuki Kurino, Hajime Mushiaki, and Misumasa Koyanagi, Intelligent Neural Implant Microsystem Fabricated Using Multi-Chip Bonding Technique, 2005 International Conference on Solid State Device and Materials, 462-463, 2005
99. Masashi Ito, Masafumi Yano, Pitch determination and sinusoidal modeling for time-varying voiced speech, The Journal of the Acoustical Society of America (4th joint meeting of ASA/ASA), 120,5,3376,2006
100. YOSHIMURA Yuki, TOMITA Nozomi, ASANO Tomotaka, MAKINO Yoshinari, YANO Masafumi, Control of Reaching Movement in Unpredictably Changing Environment by Constraints Emergence and Satisfaction, Proc. of SICE-ICASE International Joint Conference 2006, SP02-2006
101. TOMITA Nozomi, YANO Masafumi, Real-time Control of Bipedal Movement based on Basal ganglia and Brainstem Systems, Proc. of SICE-ICASE International Joint Conference 2006, 4499-4502, 2006
102. Masashi Ito, Masafumi Yano, A Local Vector Coding for High Quality Voice Analysis/Synthesis, The Journal of the Acoustical Society of America (150th Meeting of the Acoustical Society of America), 118,3,2024,2005
103. Kazuhiro Sakamoto, Toru Onizawa, Masafumi Yano, Competition between Spatial and Temporal Factors in Simple Apparent Motion is Modulated by Laterality, Proceedings of the 4th IEEE International Conference on Development and Learning (ICDL-05), 175-179, 2005
104. Yoshinari Makino, Hisanori Makinae, Tsukasa Obara, Masafumi Yano, Brain Regions Related to Odor Learning and Memory in Terrestrial Slug, *Incalia frutstorferi*: Two Lobes of the Cerebral Ganglion Show Different Spatiotemporal Activities, Proceedings of the 11th International Symposium on Artificial Life and Robotics, OS7-1, 2006
105. Kazuhiro Sakamoto, Hajime Mushiaki, Naohiro Saito, Jun Tanji, Transient Synchrony and Dynamical Representation of Behavioral Goals of the Prefrontal Cortex, Proceedings of the 4th IEEE International Conference on Development and Learning (ICDL-05), 207-211, 2005
106. Ikuo Matsuo, and Masafumi Yano, A Computational Model of Echolocation: Restoration of an Acoustic Image from a Single-Emission Echo, The Journal of the Acoustical Society of America (149th Meeting of the Acoustical Society of America), 117,4,2553,2005
107. Koji Ito, Takahiro Shoyama and Toshiyuki Kondo, Lower-limb Joint Torque and Position Controls by Functional Electrical Stimulation (FES), in J. L. Wu et al. (eds): *Complex Medical Engineering*, Springer, 240-249, 2006
108. Shunsuke Iida, Toshiyuki Kondo, Koji Ito, An Environmental Adaptation Mechanism for a Biped Walking Robot Control Based on Elicitation of Sensorimotor Constraints, From Animals to Animals 9, Lecture Notes in Computer Science, Proceedings of 9th International Conference on Simulation of Adaptive Behavior (SAB06), 4095, 174-184, 2006
109. Toshiyuki Kondo, Evolutionary design and behavior analysis of neuromodulatory neural networks for mobile robots control, *Applied Soft Computing*, 7, 189-202, 2007
110. J.L. Wu, K.Ito, S. Tobimatsu, T. Nishida, F. Fukuyama, *Complex Medical Engineering*, Springer, 2007
111. Toshiyuki Kondo, Koji Ito, A Proposal of Continuous Time Recurrent Neural Networks with Neuromodulatory Bias for Adaptation to Un-experienced Environments, SICE-ICASE Joint Conference 2006 (SICE-ICASS06), 5067-5070, 2006
112. Koji Ito, Tsutomu Imai, Naoki Torii and Toshiyuki Kondo, Decomposition of Internal Models in Motor Learning Under Mixed Dynamic Environments, SICE-ICASE Joint Conference 2006 (SICE-ICASS06), 5061-5066, 2006
113. Tomoko Nagano, Toshiyuki Kondo and Koji Ito, Distributed Motor Control System based on Spinal Cord and Musculoskeletal Mechanisms, Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 192-197, 2006
114. Koji Ito, Tsutomu Imai and Toshiyuki Kondo, Motor Adaptation to Dynamic Environments in Arm Reaching Motions, Proceedings of XVIII IMEKO WORLD CONGRESS, 2006
115. Toshiyuki Kondo, Koji Ito, A design principle of adaptive neural controllers for realizing anticipatory behavior in reaching movement under un-experienced environments, Proceedings of The Third Workshop on Anticipatory Behavior in Adaptive Learning Systems (AbALS06), 2006
116. Toshiyuki Kondo, Koji Ito, A Neuromodulatory Neural Networks Model for Environmental Cognition and Motor Adaptation, Proceedings of IEEE World Congress on Computational Intelligence (WCCI2006), 9865-9870, 2006
117. Jun Izawa, Takahito Shimizu, Toshiyuki Aoki, Toshiyuki Kondo, Hiroaki Gomi, Shigeaki Toyama, Koji Ito, MR Compatible Manipulandum with Ultrasonic Motor for fMRI Studies, Proceedings of IEEE International Conference on Robotics and Automation (ICRA2006), 3850-3854, 2006
118. Tetsunari Inamura, Naoki Koji, Masayuki Inaba, Situation Recognition and Behavior Induction based on Geometric Symbol Representation of Multimodal Sensorimotor Patterns, IEEE/RSJ International Conference on Intelligent Robots and Systems, 5147-5152, 2006
119. Tetsunari Inamura, Naoki Koji, Kazuyuki Sakamoto, Masayuki Inaba, Interactive intent initiation for humanoid robots based on dynamic attention prediction and control, 50th Anniversary Summit of Artificial Intelligence, 2006
120. Ei-ichi Izawa, Naoya Aoki, Toshiya Matsushima, Neural correlates of the proximity and quantity of anticipated food rewards in the ventral striatum of domestic chicks, *European Journal of Neuroscience*, 22, 1502-1512, 2005
121. Naoya Aoki, Ryuthei Suzuki, Ei-ichi Izawa, Andreas Csillag, Toshiya Matsushima, Localized lesions of ventral striatum, but not accumbens, enhanced impulsiveness in choices based on anticipated spatial proximity of food rewards in domestic chicks, *Behavioural Brain Research*, 168, 1-12, 2006
122. Naoya Aoki, Andreas Csillag, Toshiya Matsushima, Localized lesions of accumbens intermedium of the lateral forebrain cause a handling-cost aversion in the domestic chick performing a binary choice task, *European Journal of Neuroscience*, 24, 2314-2326, 2006
123. Toshiya Matsushima, Neural control of foraging decision making in the domestic chicks, International IBRO workshop (International Brain Research Organization, Budapest, 26 January, 2006), 2006
124. Fumihiko Ishida, Yasuji E Sawada, Semianalytical transient solution of a delayed differential equation and its application to the tracking motion in the sensory-motor system, *Physical Review E*, 7, 5, 12901, 2007
125. Kenshi Watanabe, Kenichi Ohkubo, Sumiaki Ichikawa, and Fumio Hara, Classification of Object Shapes Utilizing Tactile Spatiotemporal Differential Information Obtained from Grasping by Single-Finger Robot Hand with Soft Tactile Sensor Array, *Journal of Robotics and Mechatronics*, 19, 9, 1, 2007
126. Akira Murata, Hiroaki Ishida, Representation of bodily self in the multimodal parieto-premotor network, In: *Representation and Brain*, edited by Shintaro Funahashi, Springer Verlag, (in press)
127. Raos, V., Umiltà, M.-A., Murata, A., Fogassi, L. & Gallese, V. Functional properties of grasping-related neurons in ventral premotor area F5 of the Macaque monkey, *J Neurophysiol*, 95, 2, 709-729, 2006
128. M. Ito, K. Noda, Y. Hoshino, J. Tani, Dynamic and interactive generation of object handling behaviors by a small humanoid robot using a dynamic neural network model, *Neural Networks*, 19, 323-337, 2006
129. K. Noda, M. Ito, Y. Hoshino, J. Tani, Dynamic generation and switching of object handling behaviors by a humanoid robot using a recurrent neural network model, *Lecture Notes in Artificial Intelligence (SAB2006)*, 4095, 185-196, 2006
130. H. Arie, J. Namikawa, T. Ogata, J. Tani, S. Sugano, Reinforcement learning algorithm with CTRNN in continuous action space, *Lecture Notes in Computer Science (ICONIP2006)*, 4232, 387-396, 2006
131. Oshio Kenichi, Atsushi Chiba, Masahiko Inase, Delay Period Activity of Monkey Prefrontal Neurons during Duration-Discrimination Task, *European Journal of Neuroscience*, 23, 10, 2779-2790, 2006
132. Atsushi Chiba, Kenichi Oshio, Masahiko Inase, Cue and Delay Responses of Monkey Striatal Neurons during a Duration Discrimination Task, Proceedings of Neuroscience 2006, 36th Annual Meeting of Society for Neuroscience, 5722, 2006
133. Takakusaki K, Saitoh K and Kashiwayanagi M. The pedunculopontine nucleus and the basal ganglia in locomotion, In: *Recent Breakthroughs in Basal Ganglia Research*, (ed by E. Bezard), 133-149, 2006
134. Takakusaki K, Saitoh K, Noraka S, Okumura T, Miyokawa N, Koyama Y. Neurobiological basis of state-dependent control of motor behavior, *Sleep and Biological Rhythms*, 4, 87-104, 2006
135. Yamada H, Tanno S, Takakusaki K, Okumura T. Intracranial injection of orexin-A prevents ethanol-induced gastric mucosal damage in rats, *Journal of Gastroenterology* (in press).
136. Takakusaki K, Forebrain control of locomotor behaviors, *Brain Research Review*, (in press),
137. Adachi M, Noraka S, Katada A, Arakawa T, Ota R, Harada H, Takakusaki K, Harabuchi Y. Carbachol injection into the pontine reticular formation depresses laryngeal muscle activity and airway reflexes in decerebrate cats, *Neuroscience Research* (in press),
138. Takakusaki K, What are the Neurophysiologic Substrates of Normal and Abnormal Gait? *Journal of Neurology* (in press),
139. Takakusaki K, Forebrain control of locomotor behaviors, *Wenner-Gren Foundations International Symposium: "Networks in Motion"*, 2006
140. F. Mori, K. Nakajima, A. Tachibana, and S. Mori, Obstacle clearance and prevention from falling in the bipedally walking Japanese monkey, *Macaca fuscata*, *Age and Aging*, 35, 52, 19-23, 2006
141. F. Mori, K. Nakajima, and S. Mori, Control of bipedal walking in the Japanese monkey, *M. fuscata*, Reactive and anticipatory control mechanisms, In: Kimura, H., Tsuchiya, I., Shiguro, A., and White, H. (Eds.), *Adaptive Motion of Animals and Machines*, Springer, p. 249-p.250 (2006), 249-250, 2006
142. F. Mori, K. Nakajima, Tachibana, A., Tsukada, H., and S. Mori, Primary, supplementary and premotor cortices are involved in the execution and control of operant-trained bipedal treadmill walking in Japanese monkey (*M. fuscata*), The 1st International Congress on Gait and Mental Function
143. Satoshi Shibuya, Toshimitsu Takahashi, Shigeru Kitazawa, Effects of visual stimuli on temporal order judgments of unimanual finger stimuli, *Experimental Brain Research*, DOI 10.1007/s00221-006-0829-4, 2007
144. Kenji Yamamoto, Mitsuo Kawato, Shinya Kotaka, Shigeru Kitazawa, Encoding of movement dynamics by Purkinje cell simple spike activity during fast arm movements under resistive and force fields, *Journal of Neurophysiology*, 97, 2, 1588-1599, 2007
145. Makoto Miyazaki, Shingya Yamamoto, Sunao Uchida, Shigeru Kitazawa, Bayesian calibration of simultaneity in tactile temporal order judgment, *Nature Neuroscience*, 9, 7, 875-877, 2006
146. Makoto Wada, Kenji Yoshimi, Noriyuki Higo, Yong-Ri Ren, Hideki Mochizuki, Yoshikuni Mizuno, Shigeru Kitazawa, Statistical parametric mapping of immunopositive cell density, *Neuroscience Research*, 28, 11, 96-102, 2006
147. Nakazato T, Kagohashi M, Yoshimi M. Influence of pH on voltammetric measurement of dopamine. *Biogenic Amines*, 20, (in press), 2006
148. Shigeru Kitazawa, Reversal of subjective temporal order due to sensory and motor integrations, *Attention and Performance XXII: Sensorimotor foundations of higher cognition*, 2006
149. Shigeru Kitazawa, Where tactile signals are ordered in time, *Cognition and Action*, The 29th Annual Meeting of the Japan Neuroscience Society, 2006
150. Shigeru Kitazawa, Discussion from a neurophysiological viewpoint, Developing cross-modal representation of objects and space, *International Conference on Infant Studies 2006*, 2006
151. Kagohashi M, Moizumi S, Yoshimi K, Nakazato T, Kitazawa S, Wireless voltammetry: dopamine measurement in the freely moving rat, *Soc. Neurosci. (Suppl)* 592.1, 2006
152. Yoshimi K, Kagohashi M, Moizumi S, Hattori N, Nakazato T, Kitazawa S, Week-long voltammetric recording in the rat striatum: circadian rhythm of dopamine level, *Soc. Neurosci. (Suppl)* 469.1, 2006
153. Futoshi Mori, Katsumi Nakajima, Atsumichi Tachibana, Shigemori Mori, Obstacle Clearance and Prevention from Falling in the Bipedally Walking Japanese Monkey, *Macaca fuscata*, *Age and Aging*, 35, 52, 19-23, 2006
154. Dai Yanagihara, Role of the cerebellum in adaptive control of locomotion, Proceedings of SICE-ICASE International Joint Conference, 4493-4494, 2006
155. Nakatsukasa, M., Hirasaki, E., Ogihara, N., Energy expenditure of bipedal walking is higher than that of quadrupedal walking in Japanese macaques, *American Journal of Physical Anthropology*, 131, 33-37, 2006
156. S. Aoi, K. Tsuchiya, Bifurcation and Chaos of a Simple Walking Model Driven by a Rhythmic Signal, *International Journal of Non-Linear Mechanics*, 41, 3, 338-346, 2006
157. S. Aoi, K. Tsuchiya, Stability Analysis of a Simple Walking Model Driven by an Oscillator With a Phase Reset Using Sensory Feedback, *IEEE Transactions on Robotics*, 22, 2, 391-397, 2006
158. S. Aoi, K. Tsuchiya, Self-stability of a Simple Walking Model Driven by a Rhythmic Signal, *Nonlinear Dynamics*, 48, 1, 2-16, 2007
159. S. Aoi, K. Tsuchiya, Gait Transition from Quadrupedal to Bipedal Locomotion of an Oscillator-driven Biped Robot, *International Journal of Advanced Robotic Systems*, (in press),
160. S. Aoi, H. Sasaki, K. Tsuchiya, A Multi-legged Modular Robot That Meanders: Investigation of Turning Maneuvers Using its Inherent Dynamic Characteristics, *SIAM Journal on Applied Dynamical Systems*, (in press),
161. Nakatsukasa, M., Hirasaki, E., Ogihara, N., Energy expenditure of bipedal walking is higher than that of quadrupedal walking in Japanese macaques, *American Journal of Physical Anthropology*, 131, 33-37, 2006
162. S. Aoi, K. Tsuchiya, Bipedal Locomotion Control Using Nonlinear Oscillators, *Dynamic Walking 2006*, 2006
163. S. Aoi, K. Tsuchiya, Feedback Control of a Simple Walking Model Driven by an Oscillator, *IEEE International Conference on Robotics and Automation*, 1990-1996, 2006
164. S. Aoi, K. Tsuchiya, Turning Maneuvers of a Multi-legged Modular Robot Using Its Inherent Dynamic Characteristics, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 180-185, 2006
165. Y. Sugimoto, K. Osuka, Implicit Feedback Structure in Passive Dynamic Walking, *Dynamic Walking 2006*, 2006
166. Ogihara, N., Nakatsukasa, M., Sugimoto, Y., Aoi, S., Tsuchiya, K., Adaptive locomotion mechanisms inherent in the musculoskeletal structure, SICE-ICASE International Joint Conference 2006, 2006
167. Hase, K., Ohiwata, G., Nakayama, A., Ogihara, N., Usui, T., Tsakaki, Y., Large-scale forward dynamics simulation with a whole-body musculoskeletal model, 5th World Congress of Biomechanics, 2006
168. Zu Guang Zhang, Hiroshi Kimura and Yasuhiro Fukuko, Autonomously generating efficient running of a quadruped robot using delayed feedback control, *Advanced Robotics*, 20, 6, 607-629, 2006
169. Zu Guang Zhang, Hiroshi Kimura and Kunikatsu Takase, delayed feedback control, *Journal of Vibration and Control*, 12, 12, 1361-1383, 2006
170. Takashi Takuma, Koh Hosoda, Controlling the Walking Period of a Pneumatic Muscle Walker, *International Journal of Robotics Research*, 25, 9, 861-866, 2006
171. Hiroshi Kimura, Yasuhiro Fukuko and Avis H. Cohen, Biologically Inspired Adaptive Walking of a Quadruped Robot, *Philosophical Transactions of the Royal Society A*, 365, 1850, 153-170, 2007
172. Zu Guang Zhang, Hiroshi Kimura, and Yasuhiro Fukuko, Self-Stabilizing Dynamics for a Quadruped Robot and Extension Towards Running on Rough Terrain, *Journal of Robotics and Mechatronics*, 19, 1, 2007
173. K. Tsujita and T. Masuda, Simulation Study on Acquisition Process of Locomotion by using an Infant Robot, *International Journal of Advanced Robotic Systems*, (in press), 2006
174. K. Tsujita, A. Morioka, K. Nakatani, K. Suzuki and T. Masuda, Oscillator-controlled Bipedal Walk with Pneumatic Actuators, *KSMIE International Journal*, (in press), 2006

175. Takashi Takuma, Koh Hosoda, Controlling Walking Velocity of a Pneumatic Actuated Biped by Changing Hip Passivity, *Dynamic Walking 2006*, Poster-22/2006
176. Koh Hosoda, Takashi Takuma, and Athushi Nakamoto, Design and Control of a Running Biped with Pneumatic Artificial Muscles, *Dynamic Walking 2006*, 2006
177. Tsuyoshi UENO, Yutaka NAKAMURA, Takashi TAKUMA, Tomohiro SHIBATA, Koh HOSODA, Shin ISHII, Fast and Stable Learning of Quasi-Passive Dynamic Walking by an Unstable Biped Robot based on Off-Policy Natural Actor-Critic, *International Conference on Intelligent Robots and Systems*, 5226-5231, 2006
178. Koh Hosoda, Takashi Takuma, and Atsushi Nakamoto, Design and Control of 2D Biped that can Walk and Run with Pneumatic Artificial Muscles, *IEEE-RASRSJ International Conference on Humanoid Robots (Humanoids 2006)*, CD-ROM/2006
179. K.Tsujita, A.Morioka, K.Nakatani, K.Suzuki and T.Masuda, Oscillator-controlled Bipedal Walk with Pneumatic Actuators, *Proc. of Int. Conf. of Motion and Vibration Control*, 670-675, 2006
180. K.Tsujita and T.Masuda, Simulation of Acquisition of Locomotion of an Infant Robot, *Proc. of IEEE/RSJ IROS2006*, 4929-4934, 2006
181. Takaaki SUMI, Koussuke INOUE, Norikazu SATO, Shigen MA, Development of an Environmentally Adaptable Snake-Like Robot—Construction of a Neural Oscillator Network Capable of Changing Ground Friction—Proceedings of 3rd International Conference on Brain-Inspired Information Technology, 82/2006
182. Y. Ninomiya, Y. Kayama, Y. Koyama. Postnatal development of cholinergic neurons in the mesopontine tegmentum revealed by histochemistry. *Internat J Develop Neurosci*, 23, 711-721, 2005
183. K. Takahashi, Q.-P. Wang, J.-L. Guan, Y. Kayama, S. Shiota and Y. Koyama. State-dependent effects of orexin on the serotonergic dorsal raphe neurons in the rat. *Reg. Peptide*, 126, 43-47, 2005
184. Q.-P. Wang, Y. Koyama, J.-L. Guan, Y. Kayama, K. Takahashi, and S. Shiota. The orexinergic synaptic innervation of serotonin- and orexin-1 receptor-containing neurons in the dorsal raphe nucleus. *Reg. Peptide*, 126, 35-42, 2005
185. Y. Yasoshima, N. Kai, S. Yoshida, S. Shiosaka, Y. Koyama, Y. Kayama, Y. Koyama, Y. K. Kobayashi, Subthalamic neurons coordinate basal ganglia function through differential neural pathways. *J. Neurosci*, 25, 7743-7753, 2005
186. K. Takahashi, K. Takahashi, K. Saitoh, H. Harada, T. Okamura, Y. Kayama, Y. Koyama, Orexinergic projections to the midbrain mediate alternation of emotional behavioral states from locomotion to cataplexy. *J. Physiol.*, 568, 1003-1020, 2005
187. T. Sakurai, R. Nagata, A. Yamanaka, H. Kawamura, N. Tsujino, Y. Muraki, H. Kageyama, S. Kunita, S. Takahashi, K. Goto, Y. Koyama, S. Shiota, M. Yanagisawa, Input of orexin/hypocretin neurons revealed by genetically encoded tracer in mice. *Neuron*, 46, 297-308, 2005
188. T. Kodama, S. Usui, Y. Honda, M. Kimura, High Fos expression during the active phase in orexin neurons of a diurnal rodent, *Tamias sibiricus barberi*. *Peptides*, 26, 4631-638, 2005
189. T. Kodama, and Y. Koyama, Nitric oxide from the laterodorsal tegmental neurons: Its possible retrograde modulation on norepinephrine release from the axon terminal of the locus coeruleus neurons. *Neuroscience*, 138, 245-256, 2006
190. K. Takahashi, K. Saito, T. Nonaka, T. Okamura, N. Miyokawa, Y. Koyama, Neurobiological basis of state-dependent control of motor behaviors. *Sleep and Biological Rhythms*, 4, 87-104, 2006
191. Y. Tamakawa, A. Karashima, Y. Koyama, N. Katayama and M. Nakao, A Quartet Neural System Model Orchestrating Sleep and Wakefulness Mechanisms. *J. Neurophysiol.*, 95, 2055-2069, 2006
192. K. Takahashi, J.S. Lin, K. Sakai, Neuronal activity of histaminergic tuberomammillary neurons during wake-sleep states in the mouse. *J. Neurosci.*, 26, 4010-4022, 2006
193. K. Nakamura, Y. Koyama, K. Takahashi, et al., Requirement of tryptophan hydroxylase during development for maturation of sensorimotor gating. *J. Mol. Biol.*, 363, 345-354, 2006
194. Osamu Fukuyama, Noriyuki Taniguchi, Takafumi Suzuki, Kunihiko Mabuchi, Estimation of Locomotion Speed and Directions Changes to Control a Vehicle Using Neural Signals from the Motor Cortex of Rat, *Proceedings of the 28th IEEE EMBS Annual International Conference*, 1138-1141, 2006
195. Yasuhiro Kato, Isuro Saito, Takayuki Hoshino, Takafumi Suzuki, Kunihiko Mabuchi, Preliminary Study of Multichannel Flexible Neural Probes Coated with Hybrid Biodegradable Polymer, *Proceedings of the 28th IEEE EMBS Annual International Conference*, 660-663, 2006
196. Takashi Sato, Takafumi Suzuki, Kunihiko Mabuchi, A new multi-electrode array design for chronic neural recording, with independent and automatic hydraulic positioning. *Journal of Neuroscience Methods*, 160, 45-51, 2007
197. Sakurai, Y. How can we detect ensemble coding by cell assembly? *Representation and Brain*, 2007 (in press)
198. Sakurai, Y., Takahashi, S. Dynamic synchrony of firing in the monkey prefrontal cortex during working memory tasks. *Journal of Neuroscience*, 26, 10141-10153, 2006
199. Koike, Y., Hirose, H., Sakurai, Y., Iijima, T. Prediction of arm trajectory from a small number of neuron activities in the primary motor cortex. *Neuroscience Research*, 56, 146-153, 2006
200. Takahashi, S., Sakurai, Y. Sub-millisecond synchronization among pyramidal neurons in hippocampal CA1 of rats during delayed non-matching to sample task. *36th Society for Neuroscience Annual Meeting*, 2006
201. Hirokawa, J., M. Bosch, Sakata, S., Sakurai, Y., Yamatori, T. A distinct area of rat visual cortex mediates behavioral enhancement by audiovisual integration. *30th Society for Neuroscience Annual Meeting*, 2006
202. Sakurai, Y. Brain plasticity revealed with brain-machine interfaces. *1st International Conference on Advanced Medical Engineering and Informatics*, 2006
203. Nomura, M., Sakurai, Y., Kitano, K. & Aoyagi, T. Applying the kernel method to multi-neuronal spike trains. *1st Symposium on Complex Medical Engineering*, 2006
204. Aso T, Hanakawa T, Matsuo K, Torna K, Shibasaki H, Fukuyama H, Nakai T. Subregions of human parietal cortex selectively encoding object orientation. *Neuroscience Letters*, (in press)
205. Sawamoto N, Honda M, Hanakawa T, Aso T, Inoue M, Toyoda H, Ishizu K, Fukuyama H, Shibasaki H. Role of the striatum in cognitive slowing in Parkinson's disease. *Neurology*, (in press)
206. Yamada M, Namiki C, Hirao K, Hanakawa T, Fukuyama H, Hayashi T, Murai T. Social cognition and frontal lobe pathology in schizophrenia: A voxel-based morphometric study. *Neuroimage*, (in press)
207. Mikuni N, Okada T, Nishida N, Taki J, Eratsu R, Ikeda A, Miki Y, Hanakawa T, Fukuyama H, Hashimoto N. Comparison between motor evoked potential recording and fiber tracking for estimating pyramidal tracts near brain tumors. *Journal of Neurosurgery*, 106, 1128-133, 2007
208. Yamamoto A, Miki Y, Urayama S, Fushimi Y, Okada T, Hanakawa T, Fukuyama H, Togashi K. Diffusion tensor fiber tractography of the optic radiation: analysis with 6-, 12-, 40- and 81-directional motion probing gradients: a preliminary study. *American Journal of Neuroradiology*, 28, 192-96, 2007
209. Mikuni N, Okada T, Taki J, Matsumoto R, Nishida N, Eratsu R, Hanakawa T, Ikeda A, Miki Y, Urayama S, Fukuyama H, Hashimoto N. Fibers from the dorsal premotor cortex elicit motor-evoked potential in a cortical dysplasia. *Neuroimage*, 34, 1, 12-18, 2007
210. Takaya S, Hanakawa T, Hashikawa K, Ikeda A, Sawamoto N, Nagamine T, Ishizu K, Fukuyama H. Prefrontal hypofunction in patients with intractable mesial temporal lobe epilepsy. *Neurology*, 67, 9, 1674-1676, 2006
211. Kikuta K, Takagi Y, Fushimi Y, Ishizu K, Okada T, Hanakawa T, Miki Y, Fukuyama H, Nozaki K, Hashimoto N. "Target bypass": a method for preoperative targeting of a recipient artery in superficial temporal artery-to-middle cerebral artery anastomoses. *Neurosurgery*, 59, 4, ON3-320-327, 2006
212. Okada T, Miki Y, Mikuni N, Kikuta K, Urayama S, Hanakawa T, Fukuyama H, Hashimoto N, Togashi K. Diffusion tensor tractography of corticospinal tract using 3-T combined with white matter stimulation mapping: an integrated approach to validate the corticospinal tract localization. *Radiology*, 240, 3, 849-857, 2006
213. Fukui H, Murai T, Shinozaki J, Aso T, Fukuyama H, Hayashi T, Hanakawa T. The neural basis of social tactics: An fMRI study. *Neuroimage*, 32, 913-920, 2006
214. Bohlhalter S, Goldfine A, Matteson A, Gaux G, Hanakawa T, Kansaku K, Wurzman R, Hallett M. Neural correlates of tic generation in Tourette syndrome: an event-related functional MRI study. *Brain*, 129, 8, 2019-37, 2006
215. Callan D, Tsytsev V, Hanakawa T, Callan A, Katsuhara M, Fukuyama H, Turner R. Perception and covert generation of song and speech. *Neuroimage*, 31, 3, 1327-1342, 2006
216. Crinion J, Turner R, Grogan A, Hanakawa T, Noppeney U, Devlin JT, Aso T, Urayama S, Fukuyama H, Stockton K, Usui K, Green D, Price CJ. Language control in the bilingual brain. *Science*, 312, 5779, 1537-1540, 2006
217. Hanakawa T, Honda M, Zito G, Dinyan MA, Hallett M. Brain activity during motor behavior triggered by arbitrary cues and spatially-constrained cues: An fMRI study in humans. *Experimental Brain Research*, 172, 2, 275-282, 2005
218. Le Bihan D, Urayama S, Aso T, Hanakawa T, Fukuyama H. Direct and fast detection of neuronal activation in the human brain with diffusion MRI. *Proceedings of National Academy of Science USA*, 103, 21, 8263-8268, 2006
219. Fushimi Y, Miki Y, Kikuta K, Okada T, Kanagaki M, Yamamoto A, Nozaki K, Hashimoto N, Hanakawa T, Fukuyama H, Togashi K. Comparison of 3.0- and 1.5-T three-dimensional time-of-flight MR angiography in moyamoya disease: a preliminary experience. *Radiology*, 239, 1, 232-237, 2006
220. Kikuta K, Takagi Y, Nozaki K, Hanakawa T, Okada T, Fushimi Y, Miki Y, Fukuyama H, Hashimoto N. Early experience with 3tesla magnetic resonance tractography in the surgery of cerebral AVMs in and around the visual pathway. *Neurosurgery*, 58, 2, 331-337, 2006
221. Gaux G, Goldfine A, Bohlhalter S, Lerner A, Hanakawa T, Hallett M. The midbrain hypothesis in Tourette's syndrome: a reappraisal using voxel-based morphometry. *Annals of Neurology*, 59, 2, 381-385, 2006
222. Okada T, Miki Y, Fushimi Y, Hanakawa T, Kanagaki M, Yamamoto A, Urayama S, Fukuyama H, Hirakawa M, Togashi K. Diffusion tensor fiber tractography: Intra-individual comparison using 3 T and 1.5 T MRI. *Radiology*, 238, 2, 668-678, 2006
223. Fridman E, Immrich I, Hanakawa T, Bohlhalter S, Waldvogel D, Kansaku K, Wheaton L, Wu T, Hallett M. The role of the dorsal stream for gesture production. *Neuroimage*, 29, 2, 417-428, 2006
224. Hanakawa T. Neuroimaging of standing and walking: Special emphasis on Parkinsonian gait. *Parkinsonism and Related Disorders*, 12, Suppl 2, S70-75, 2006
225. Ihara M, Tomimoto H, Ishizu K, Yoshida H, Sawamoto N, Hashikawa K, Fukuyama H. Association of vascular parkinsonism with impaired neuronal integrity in the striatum. *Journal of Neural Transmission*, (in press)
226. Miyamoto JJ, Honda M, Saito DN, Okada T, Ono T, Ohyama K, Sadato N. The representation of the human oral area in the somatosensory cortex: a functional MRI study. *Cerebral Cortex*, 16, 5, 669-675, 2006
227. Qiu Y, Noguchi Y, Honda M, Nakata H, Tamura Y, Tanaka S, Sadato N, Wang X, Inui K, Kakigi R. Brain processing of the signals ascending through unmyelinated C fibers in humans: an event-related functional magnetic resonance imaging study. *Cereb Cortex*, 16, 9, 1289-1295, 2006
228. Aramaki Y, Honda M, Okada T, Sadato N. Neural correlates of the spontaneous phase transition during bimanual coordination. *Cereb Cortex*, 16, 9, 1338-1348, 2006
229. Aramaki Y, Honda M, Sadato N. Suppression of the non-dominant motor cortex during bimanual symmetric finger movement: a functional magnetic resonance imaging study. *Neuroscience*, 141, 4, 2147-2153, 2006
230. Saito DN, Okada T, Honda M, Yonekura Y, Sadato N. Practice makes perfect: the neural substrates of tactile discrimination by Mah-Jong experts include the primary visual cortex. *BMC Neurosci*, 5, 77, 2006
231. Kiyoji Matsuyama K, Suguru Kobayashi, Mamoru Aoki. Projection patterns of lamina VIII commissural neurons in the lumbar spinal cord of the adult cat: an anterograde axonal tracing study. *Neuroscience*, 140, 1, 203-218, 2006
232. Ying Cao, Yutaka Fujio, Kiyoji Matsuyama, Mamoru Aoki. Effects of electrical stimulation of the medullary raphe nuclei on respiratory movements in rats. *Journal of Comparative Physiology A: Sensory, Neural, and Behavioral Physiology*, 192, 5, 497-505, 2006
233. Ying Cao, Kiyoji Matsuyama, Yutaka Fujio, Mamoru Aoki. Involvement of medullary GABAergic and serotonergic raphe neurons in respiratory control: electrophysiological and immunohistochemical studies in rats. *Neuroscience Research*, 56, 3, 322-331, 2006
234. Kiyoji Matsuyama, Masanori Ishiguro, Suguru Kobayashi, Mamoru Aoki. Characteristics of the interlimb coordination between fore- and hindlimbs during hopping movements in decerebrate rabbits. *Neuroscience Meeting Planner of Neuroscience 2006 (36th Annual Meeting of the Society for Neuroscience)*, 648, 14, 2006
235. M. Nakanishi, T. Nomura, S. Sato. Stumbling with optimal phase reset during gait can prevent a humanoid from falling. *Biological Cybernetics*, 95, 5, 503-515, 2006
236. Y. Yasutake, S. Taniguchi, T. Nomura. Non-Asymptotic Postural Stabilization Strategy during Human Quiet Stand. *Proceedings of the 28th IEEE EMBS Annual International Conference*, New York City, USA, Aug 30-Sept 3, 1189-1192, 2006
237. T. Ishikawa, Y. Kaji, T. Nomura. Sensory perception of unexpected sudden changes in floor level during human gait. *Proceedings of the 28th IEEE EMBS Annual International Conference*, New York City, USA, Aug 30-Sept 3, 4474-4477, 2006
238. Kazuhiko SEKI, Tomohiko TAKEI. Primary afferent depolarization evoked by natural stimulation of cutaneous afferent in monkey. *006 Neuroscience Meeting Planner*. Atlanta, GA: Society for Neuroscience, 2006. Online, 627-54.8P13628.2006
239. Tomohiko Takei, Kazuhiko SEKI. Involvement of the primate spiral neurons in the control of precision grip. *006 Neuroscience Meeting Planner*. Atlanta, GA: Society for Neuroscience, 2006. Online, 54.9P14.2006
240. Tomohiko Takei, Kazuhiko SEKI. Spino-muscular coherence in monkey performing a precision grip task. *Society for neural control of movement annual meeting abstract booklet*, (in press), 2007
241. Ot S. R., Aonuma H., Newland PL. and Elphick MR. Nitric oxide synthase in crayfish walking leg ganglia: segmental differences in chemo-tactile centers argue against a generic role in sensory integration. *J. Comp. Neurol.*, 501, 381-399, 2007
242. Watanabe T, Kikuchi M, Hatakeyama D, Shiga T, Yamamoto T, Aonuma H, Takahata M, Suzuki N, and Ito E. Gaseous neuromodulator-related genes expressed in the brain of honeybee *Apis mellifera*. *Develop. Neurobiol.*, (in press), 2007
243. Ikono H, Nishioka T, Hachida T, Kanzaki R, Seki Y, Ohtzawa I, Usui S. Development and application of CMS based database modules for neuroinformatics. *Neurocomputing*, (in press), 2007
244. Waga-tsuma A, Azami S, Sakura M, Hatakeyama D, Aonuma H. and Ito E. De novo synthesis of CREB in a presynaptic neuron is required for synaptic enhancement involved in memory consolidation. *J. Neurosci. Res.*, 84, 954-960, 2006
245. Matsumoto Y, Unoki S., Aonuma H. and Mizunami M. Nitric oxide-cGMP signaling is critical for cAMP-dependent long-term memory formation. *Learn. Mem.*, 13, 1, 35-44, 2006
246. Delgado A. and Aonuma H. Experience based agonistic behavior in female crickets, *Gryllus bimaculatus*. *Zool. Sci.*, 23, 775-783, 2006
247. Iwasaki M, Delgado A., Nishino H. and Aonuma H. Effects of previous experiences on the agonistic behaviour of male crickets *Gryllus bimaculatus*. *Zool. Sci.*, 23, 863-872, 2006
248. Niwa K, Sakai J, Karino T, Aonuma H, Watanabe T, Ohyama T, Inanami O. and Kuwahara M. Reactive oxygen species mediate shear stress-induced fluid-phase endocytosis in vascular endothelial cells. *Free Radical Res.*, 40, 2, 167-174, 2006
249. Yamasaki T, Isokawa T, Matsui M, Ikono H and Kanzaki R. Reconstruction and simulation for three-dimensional morphological structure of insect neurons. *Neurocomputing*, 69, 1043-1047, 2006
250. Kitamura Y, Aonuma H, Oka K. and Ogawa H. Acetylcholine enhances nitric oxide production in the terminal abdominal ganglion of the cricket, *Gryllus bimaculatus*. *Society for Neuroscience*, 351, 2006
251. Suzuki M, Kitamura T, Ogawa H, Aonuma H, Kitamura Y, Hotta K. and Oka K. Peripheral nervous plexuses control squid chromatophore organs. *Society for Neuroscience*, 353, 2006
252. Tomohisa Fujiki, Kuniaki Kawabata, Hajime Asama. Adaptive Action Selection of Body Expansion Behavior in Multi-Robot System using Communication. *Journal of Advanced Computational Intelligence and Intelligent Informatics*, 11, 2, 2007
253. Yusuke Fukazawa, Chomchana Tevai, Jun Ota and Tamio Arai. Acquisition of Intermediate Goals for an Agent Executing Multiple Tasks. *IEEE Transactions on Robotics*, 22, 5, 1034-1040, 2006
254. T. Fujiki, K. Kawabata, H. Aonuma, H. Asama. A Computational Model of the Adaptive Action Selection in Cricket Fighting Behavior by NO/cGMP Cascade. *The 2nd International Workshop by Research Group of Invertebrate Nervous System of Japan*, 8, 2006
255. Ashikaga, M., Hiraguchi, T., Sakura, M., Aonuma, H. and Ota, J. Modeling of Adaptive Behaviors of Crickets. *5th Forum of European Neuroscience Abstract Book (FENS Forum Abstracts)*, 3, A1291, 2006
256. M. Ashikaga, M. Kikuchi, T. Hiraguchi, M. Sakura, H. Aonuma and J. Ota. Modeling of fighting behaviors in crickets. *The 2nd International Workshop by Research Group of Invertebrate Nervous System of Japan*, 7, 2006
257. Yusuke Tamura, Masao Sugi, Jun Ota and Tamio Arai. Prediction of Target Object Based on Human Hand Movement for Handing-Over between Human and Self-Moving Trays. *Proc. 15th IEEE Int. Symp. Robot and Human Interactive Communication (RO-MAN'06)*, 189/194, 2006
258. Yusuke Tamura, Masao Sugi, Jun Ota and Tamio Arai. Handing-over between Human and Self-Moving Tray. *Proc. XVIII IMEKO World Congress Metrology for a Sustainable Development*, 2006
259. Daisuke Kurabayashi, Katsunori Urano, Tetsuro Funato, Tetsuro Funato. Emergent Transportation Networks by Considering Interactions between Agents and their Environment. *Advanced Robotics*, (in press), 2007
260. Daisuke Kurabayashi, Kunio Okita, Tetsuro Funato. Obstacle avoidance of a mobile robot group using a nonlinear oscillator network. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 186-191, 2006
261. Tetsuro Funato, Hiroshi Aonuma, Daisuke Kurabayashi, Masahito Nara. Development of oscillator network model for behavioral processing. *2nd International Workshop by Research Group of Invertebrate Nervous System of Japan*, 29-31, 2006
262. Tetsuro Funato, Daisuke Kurabayashi, Masahito Nara. Synchronization Control by Structural Modification of Nonlinear Oscillator Network. *8th International Symposium on Distributed Autonomous Robotic Systems*, 41-50, 2006
263. Daisuke Kurabayashi, Tomohiro Inoue, Akira Yajima, Tetsuro Funato. Emergence of small-world in Ad-hoc communication network among individual agents. *Intelligent Autonomous Systems 9*, 605-612, 2006

264. Comette R, Koshikawa, S, Hojo M, Matsumoto T, Miura T, A caste-specific cytochrome P450 in the damp-wood termite *Hodotermopsis sjostedii* (Isoptera, Termitidae). *Insect Molecular Biology*, 15, 235-244, 2006
265. Garcia J, Maekawa K, Constantino R, Matsumoto T, Miura T, Analysis of the genetic diversity of *Nasutitermes coxipensis* (Isoptera: Termitidae) in natural fragments of Brazilian cerrado savanna using AFLP markers. *Sociobiology*, 48, 267-279, 2006
266. Miura T, Caste development and division of labor in the processionary nasute termite *Hopliatitermes medioflavus* in Borneo. *TROPICS*, 15, 275-278, 2006
267. Okada Y, Tsuji K, Miura T, Morphological differences between sexes in the ponerine ant *Diacamma* sp. (*Diacamma*: Ponerinae). *Sociobiology*, 48, 527-541, 2006
268. Hojo M, Matsumoto T, Miura T, Cloning and expression of a geranylgeranyl diphosphate synthase gene - Insights into the synthesis of termite defense secretion. *Insect Molecular Biology*, 16, 121-131, 2007
269. Katoh H, Matsumoto T, Miura T, Alate differentiation and compound-eye development in the dry-wood termite *Neotermes kosshunensis* (Isoptera, Kalotermitidae). *Insectes Sociaux*, 54, (in press), 2007
270. T. Miura, Heterochrony and modularity of the caste polyphenism in termites, XV Congress IUSI Proceedings, 103, 2006
271. R. Comette, S. Koshikawa, T. Matsumoto, T. Miura, Juvenile hormone and caste differentiation in the damp-wood termite *Hodotermopsis sjostedii*: histological and molecular approaches focused on the soldier differentiation, XV Congress IUSI Proceedings, 36-37, 2006
272. S. Koshikawa, T. Miura, Gene expression analysis during caste differentiation in the damp-wood termite - perspective for genome-wide analysis, XV Congress IUSI Proceedings, 104, 2006
273. S. Miyazaki, T. Murakami, N. Azuma, S. Higashi, T. Miura, Soldier-specific modification of the mandibular motor neurons in termites, XV Congress IUSI Proceedings, 255, 2006
274. Y. Ishikawa, T. Miura, Soldier-specific modification of the mandibular motor neurons in termites, XV Congress IUSI Proceedings, 872-873, 2006
275. A. Ishikawa, T. Miura, Developmental regulation of the wing polyphenism in aphids, XV Congress IUSI Proceedings, 229, 2006
276. M. Hojo, T. Matsumoto, T. Miura, Geranylgeranyl diphosphate synthesis is related to the biosynthesis of defensive secretion in *Nasutitermes takasagoensis* (Isoptera: Termitidae), XV Congress IUSI Proceedings, 222, 2006
277. K. Maekawa, S. Mizuno, S. Koshikawa, T. Miura, Compound eye development during caste differentiation in the termite *Reticulitermes speratus* (Isoptera: Rhinotermitidae), XV Congress IUSI Proceedings, 225, 2006
278. T. Matsumoto, T. Miura, S. Koshikawa, R. Comette, K. Maekawa, O. Kitade, T. G. Myles, Phylogeny, evolution and colony composition of the primitive damp-wood termites (Termitinae, Termitidae, Isoptera) in Asia and North America, XV Congress IUSI Proceedings, 178-179, 2006
279. Takeuchi, H., Paul, R. K., Matsuzaka, E., and Kubo, T., EcR-A expression in the brain and ovary of the honeybee. *Zool. Sci.*, (in press), 2007
280. Uno, Y., Fujiyuki, T., Takeuchi, H., Morioka, M., and Kubo, T., Identification of proteins whose expression is up- or down-regulated in the mushroom bodies in the honeybee brain using proteomics. *FEBS Lett.*, 581, 197-101, 2007
281. Hideaki Takeuchi, Gene expression in the Honeybee Brain Mushroom Body and its Gene Orthologues. Evolution of Nervous Systems (Elsevier), 1, 457-469, 2006
282. Fujiyuki, T., Ohka, S., Takeuchi, H., Omo, M., Nomoto, A., and Kubo, T., Prevalence and phylogeny of Kakugo virus, a novel insect picorna-like virus that infects the honeybee (*Apis mellifera* L.), under various colony conditions. *J. Virol.*, 80(23), 11528-11538, 2006
283. Paul, R. K., Takeuchi, H., and Kubo, T., Expression of two ecdysteroid-regulated genes, Broad-Complex and *E75*, in the brain and ovary of the honeybee (*Apis mellifera* L.). *Zool. Sci.*, 23, 121085-1092, 2006
284. Kuniieda, T., Fujiyuki, T., Kucharski, R., Foret, S., Ament, S. A., Toth, A. L., Ohnishi, K., Takeuchi, H., Kamikouchi, A., Kage, E., Morioka, M., Beyre, M., Kubo, T., Robinson, G. E., Maleszka, R., Carbohydrate metabolism genes and pathways in insects: insights from the honey bee genome. *Insect Mol. Biol.*, 15, 563-576, 2006
285. Yamazaki, Y., Shirai, K., Paul, R. K., Fujiyuki, T., Wakamoto, A., Takeuchi, H., and Kubo, T., Differential expression of HR38 in the mushroom bodies of the honeybee brain depends on the caste and division of labor. *FEBS Lett.*, 580(11), 2667-2770, 2006
286. Hori, S., Takeuchi, H., Arikawa, K., Kinoshita, M., Ichikawa, N., Sasaki, M., and Kubo, T., Associative visual learning, color discrimination, and chromatic adaptation in the harnessed honeybee *Apis mellifera* L. *J. Comp. Physiol. A*, 192, 691-700, 2006
287. Lehman, H. K., Schulz, D. J., Barron, A. B., S. A., Wright, L., Hardison, C., Whirey, S., Takeuchi, H., Paul, R. K., and Robinson, G. E., Division of labor in the honey bee (*Apis mellifera*): The role of tyramine beta-hydroxylase. *J. Exp. Biol.*, 209, 14, 2774-2784, 2006
288. The Honeybee Genome Sequencing Consortium, Insights into social insects from the genome of the honey bee *Apis mellifera*. *Nature*, 443, 711, 931-949, 2006
289. Mamiko Ozaki, Ant nestmate and non-nestmate discrimination by a sensillum, 15th International Union for the Study of Social Insects, 130, 2006
290. Wakako Omura, Mamiko Ozaki, Ryohei Yamakura, Behavioral and electrophysiological investigation on taste response of the termite *Zootermopsis nevadensis* to wood extracts. *Wood Sci.*, 52, 261-264, 2006
291. Kazumitsu Hanaï, Mamiko Ozaki, Daigo Yamamura, Yasuhiro Nakatomi, Chihiro Yokoyama and Kenji Fukui, Scale free dynamics involved in the locomotion activity of ant and mouse. *WSEAS Transactions on Biology and Biomedicine*, 3, 511-515, 2006
292. Takayuki Watanabe, Mika Kikuchi, Dai Hatakeyama, Takumi Shiga, Takehiro Yamamoto, Hitoshi Aonuma, Masakazu Takahata, Norio Suzuki, and Etsuro Ito, Gaseous neuromodulator-related genes expressed in the brain of honeybee *Apis mellifera*. *Developmental Neurobiology*, (in press),
293. Takayuki Yamazaki, Teijiro Isokawa, Nobuyuki Matsui, Hidetoshi Ikeno, Ryohei Karzaki, Reconstruction and simulation for three-dimensional morphological structure of insect neurons. *Neurocomputing*, 69, 1043-1047, 2006
294. Hidetoshi Ikeno, Takuto Nishioka, Takuya Hachida, Ryohei Karzaki, Yoichi Seki, Izumi Ohzawa, Shiro Usui, Development and application of CMS based database modules for neuroinformatics. *Annual Computational Neuroscience Meeting 2006*, 60, 2006
295. Tachiro Taniguchi, Tetsuo Sawaragi, Incremental Acquisition of Behaviors and Signs based on Reinforcement Learning Schema Model and STDP. *Advanced Robotics*, (in press), 2007
296. Tetsuo Sawaragi, Yukio Horiguchi and Yuji Kuroda, Editing and Distributing Human Skills within community via Fragmentary Annotations on Image Data. Preprints of the 8th IFAC Symposium on Automated Systems Based on Human Skill and Knowledge, CD-ROM, 2006
297. Tetsuo Sawaragi and Yukio Horiguchi, Human-Robot Collaboration: Technical Issues from a Viewpoint of Human-Centered Automation. *Proc. of International Symposium on Automation and Robotics in Construction 2006*, CD-ROM, 2006
298. Tetsuo Sawaragi, Yukio Horiguchi and Akihiro Hira, Safety Analysis of Systemic Accidents Triggered by Performance Deviation. *Proceedings of SICE-ICASE International Joint Conference 2006*, 1778-1781, 2006
299. Yukio Horiguchi, Ryuichi Fukui and Tetsuo Sawaragi, An Estimation Method of Possible Mode Confusion in Human Work with Automated Control Systems. *Proceedings of SICE-ICASE International Joint Conference 2006*, 943-948, 2006
300. T. Taniguchi, T. Sawaragi, Symbol emergence by combining a reinforcement learning schema model with asymmetric synaptic plasticity. *Proceedings in 5th International Conference on Development and Learning*, CD-ROM, 2006
301. T. Taniguchi, T. Sawaragi, Incremental Acquisition of Compositional Schemata based on Behavioral Learning. *Proceedings of 6th International Workshop on Epigenetic Robotics*, 187, 2006
302. Kazuki Tsuji, Tomonori Sasaki, Hideaki Mori, Shigetō Dobata, Eisuke Hasegawa — Evolutionary Dynamics of altruists vs. social parasites in the ant *Pristomyrmex punctatus*, XV IUSI (the International Union for the study of social insects) Congress Proceedings, 122, 2006
303. Kazuki Tsuji, Hisashi Ohsaki, Reproductive allocation conflict causes worker policing in hymenopteran societies, XV IUSI Congress Proceedings, 131, 2006
304. Yasukazu Okada, Kazuki Tsuji, Toru Miura, Behavioral ontogeny followed by reproductive division of labor in the Japanese ponerine ant *Diacamma* sp., XV IUSI Congress Proceedings, 246, 2006
305. Shigetō Dobata, Tomonori Sasaki, Masakazu Shimada, Kazuki Tsuji, Spatially explicit model for altruist-cheater population dynamics in the ant *Pristomyrmex punctatus*, XV IUSI Congress Proceedings, 256, 2006
306. Mayuko Suwabe, Hitoshi Ohnishi, Tomonori Kikuchi, Kazuki Tsuji, Distribution and seasonal activity patterns of exotic and native ants in Okinawa island, XV IUSI Congress Proceedings, 263, 2006
307. J. Le Breton, G. Takaku, K. Tsuji, Brood parasitism in an invasive population of the pest ant *Pheidole megacephala*. *Insectes Sociaux*, 53, 2, 168-171, 2006
308. Kikuchi, T., Tsuji, K., Ohnishi, H., Le Breton, J., Caste-biased acceptance of non-nestmates in a polygynous ponerine ant, *Animal Behaviour*, (in press), 2007
309. Kazuki Tsuji, Life history strategy and evolution of insect societies: age structure, spatial distribution and density dependence. V. E. Kipyatkov (ed.): *Life Cycles in Social Insects: Behaviour, Ecology and Evolution*. St. Petersburg University Press, St. Petersburg, 156 p., 21-36, 2006
310. K. Oka, A. Fujimura, K. Hotta, H. Ogawa, Analysis of vocal communication between male and female zebra finches. *Fifth East Asian Biophysics Symposium & Forty-Fourth Annual Meeting of the Biophysical Society of Japan*, 2P370, 2006
311. Tomoko Akiyama, Motochiro Kato, Taro Muramatsu, Satoshi Umeda, Fumie Saito, Haruo Kashima, Unilateral amygdala lesions hamper attentional orienting by gaze direction. *Cerebral Cortex*, (in press), 2007
312. Tomoko Akiyama, Motochiro Kato, Taro Muramatsu, Takaki Maeda, Tsunekazu Hara, Haruo Kashima, Gaze-triggered orienting is reduced in chronic schizophrenia. *Psychiatry Research*, (in press), 2007
313. K. Sasaki and K. Asaka, Swallowing motor pattern triggered and modified by taste information in larvae of the silkworm, *Bombyx mori*. *Journal of Insect Physiology*, 52, 528-537, 2006
314. H. Shiga, J. Murakami, T. Nagao, M. Tanaka, K. Kawahara, I. Matsuoka and E. Ito, Glutamate release from astrocytes is stimulated via the appearance of exocytosis during cyclic AMP-induced morphologic changes. *Journal of Neuroscience Research*, 84, 338-347, 2006
315. K. Sasaki and K. Harano, Potential effects of tyramine on the transition of reproductive workers in honeybees (*Apis mellifera* L.). *Physiological Entomology*, 32, (in press), 2007
316. K. Harano, M. Sasaki and K. Sasaki, Effects of reproductive state on rhythmicity, locomotor activity and body weight in European honeybee, *Apis mellifera* (Apidae: Hymenoptera) queens. *Sociobiology*, 49, (in press), 2007
317. J. Murakami, H. Aonuma and T. Nagao, Nitric oxide mediated biogenic amine system in the agonistic behavior of cricket. *KIT International Symposium on Brain and Language 2005*, 23, 2006
318. K. Harano, K. Sasaki and T. Nagao, Dopamine levels associated with physiological and behavioral changes after mating in European honeybee queens. *8th Asian Australian Apicultural Conference Proceedings*, 32, 2006
319. K. Harano, K. Sasaki, T. Nagao and M. Sasaki, Decline of dopamine levels after mating and its association with behavioral changes in European honeybee queens. *11th Biological Sciences Graduate Congress Proceedings*, 18, 2006
320. K. Sasaki, K. Yamazaki and T. Nagao, Physiological correlates of brain biogenic amines with dominance and reproductive behaviors in primitive paper wasps *Polistes chinensis*. *KIT International Symposium on Brain and Language Proceedings*, 28-29, 2006
321. K. Harano, K. Sasaki and T. Nagao, Dopamine levels associated with physiological and behavioral changes after mating in European honeybee queens. *KIT International Symposium on Brain and Language Proceedings*, 24-25, 2006
322. T. Nariia, K. Harano and K. Sasaki, Involvement of dopamine and its receptor with transition of reproductive states in honeybee workers. *KIT International Symposium on Brain and Language Proceedings*, 21-22, 2006
323. M. Sugiyama, K. Sasaki, T. Nagao and K. Iwabuchi, Involvement of biogenic amines with escape behaviors of host *Acanthopiles agnata* parasitized by endoparasitic wasp *Glyptapanteles pallipes*. *KIT International Symposium on Brain and Language Proceedings*, 26-27, 2006
324. Y. Tamori and N. Tomita, Orbital representation of auditory perception. *The 10th meeting of Association for the Scientific Study of Consciousness*, 2006
325. K. Mogi and Y. Tamori, Making good hidden figures. *The 29th European Conference on Visual Perception*, 2006
326. K. Sasaki, Reorganization of the central nervous system responding to changes in social environment in insects. *ESB Special Seminar*, 2007
327. Hihara, S., Notoya, T., Tanaka, M., Ichinose, S., Ojima, H., Obayashi, S., Fujii, N., Inki, A. Extension of corticocortical afferents into the anterior bank of the intraparietal sulcus by tool-use training in adult monkeys. *Neuropsychologia*, 44, 13, 2636-46, 2006
328. N. Fujii, S. HIHARA, A. IRIKI, Conflicting social environment represented in primate parietal cortex. *Atlanta, GA: Society for Neuroscience*, 2006, 63.6, 2006
329. N. FUJII, D. ABLA, N. KUDO, S. HIHARA, K. OKANOYA, A. IRIKI, Prefrontal cortex manipulates abstract object knowledge. *Atlanta, GA: Society for Neuroscience*, 2006, 263.17, 2006
330. M. Inbe, K. Osuka, Analogy between passive walking robot and Phase Locked Loop circuit. *Proceedings of the SICE-ICASE International Joint Conference 2006 (SICE-ICASS 2006)*, C D, 2006
331. M. Inbe, K. Osuka, Analysis and stabilization of the passive walking robot via analogy with the Phase Locked Loop circuit. *Proceedings of the IEEE-RASRSJ International Conference on Humanoids Robots (Humanoids 2006)*, C D, 2006
332. M. Inbe, K. Osuka, A designing method of the passive dynamic walking robot via analogy with the Phase Locked Loop circuit. *Proceedings of the 2006 IEEE International Conference on Robotics and Biomimetics (ROBIO2006)*, C D, 2006
333. Akio Ishiguro, Hiroaki Matsuba, Tomoki Megawa, Masahiro Shimizu, A Modular Robot That Self-Assembles. *Intelligent Autonomous Systems 9*, 585-594, 2006
334. Akio Ishiguro, Masahiro Shimizu, Toshihiro Kawakatsu, A Modular Robot That Exhibits Amoebic Locomotion. *Robotics and Autonomous Systems*, 54, 641-650, 2006
335. Akio Ishiguro, *Mobility: The Emergence of Adaptive Motor Function through Interaction Among the Body, Brain, and Environment*. *50th Anniversary Summit of Artificial Intelligence*, 2006
336. Masahiro Shimizu, Takafumi Mori, Akio Ishiguro, A Development of a Modular Robot That Enables Adaptive Reconfiguration. *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 174-179, 2006
337. Akio Ishiguro, Tomoki Maegawa, Self-Assembly Through the Interplay between Control and Mechanical Systems. *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 631-638, 2006
338. Takuya Umedachi, Akio Ishiguro, A Development of a Fully Self-contained Real-time Tunable Spring. *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 1662-1667, 2006
339. Dai Owaki, Akio Ishiguro, Enhancing Stability of a Passive Dynamic Running Biped by Exploiting a Nonlinear Spring. *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 4923-4928, 2006
340. Tomoki Maegawa, Akio Ishiguro, Self-reconfiguration by a Modular Robot That Has a Cell-differentiation Ability. *SICE-ICASE International Joint Conference 2006*, 2073-2077, 2006
341. Masahiro Shimizu, Takafumi Mori, Toshihiro Kawakatsu, Akio Ishiguro, An Adaptive Morphology Control of a Modular Robot. *SICE-ICASE International Joint Conference 2006*, 4509-4514, 2006
342. Dai Owaki, Akio Ishiguro, Enhancing Self-stability of a Passive Dynamic Runner by Exploiting Nonlinearity in the Leg Elasticity. *SICE-ICASE International Joint Conference 2006*, 4532-4537, 2006
343. H. Shioya, K. Gohara, Generalized phase retrieval algorithm based on information measures. *Optics Communications*, 266, 1, 88-93, 2006
344. M. Nagayama, T. Uchida, K. Gohara, Temporal and Spatial variations of Lipid Droplets during Adipocyte Division and Differentiation. *J. Lipid Res.*, 48, 1, 9-18, 2007
345. K. Gohara, Fractals in Hybrid Systems. *Proceedings of Nonlinear Theory and Application*, 171-174, 2006
346. M. Uchida, Y. Maehara, H. Shioya and W.T. Huang, Unsupervised Weight Parameter Estimation Method for Ensemble Learning. *Proceedings of Joint 3rd International Conference on Soft computing and Intelligent systems and 7th International Symposium on advanced Intelligent Systems (SCIS & ISIS 2006)*, 416-421, 2006
347. D. Kitakoshi, H. Shioya and R. Nakano, Stochastic Information Expressed in a Mixture Model of Bayesian Networks - Applying to Adaptive Learning for Mobile Robots in Actual Environments. *Proceedings of Joint 3rd International Conference on Soft computing and Intelligent systems and 7th International Symposium on advanced Intelligent Systems (SCIS & ISIS 2006)*, 636-643, 2006
348. H. Diebner and I. Tsuda, Fundamental Interfaciology: Indistinguishability and Time's arrow. *Proceedings of the Foundation of Information Science 2005*, 1-16, 2005
349. H. Fujii and I. Tsuda, Interneurons: their cognitive roles - A perspective from dynamical systems view. *The Fourth IEEE International Conference in Development and Learning - from Interaction to Cognition*, 1-6, 2005
350. Y. Yamaguti, S. Kuroda and I. Tsuda, A mathematical model for the hippocampus: toward the understanding of episodic memory. *Abstracts: The 8th RIES-Hokudai International Symposium on [bi]*, 108-109, 2006
351. K. Matsumoto and I. Tsuda, Controlling engine data: Nonperiodic fluctuations in a spark ignition engine of motorcycle and its stabilization. *Abstracts: The 8th RIES-Hokudai International Symposium on [bi]*, 110-111, 2006
352. S. Tadokoro, Y. Yamaguti, I. Tsuda and H. Fujii, Chaotic itinerancy in gap junction-coupled class I<sup>+</sup> neurons. *Abstracts: The 8th RIES-Hokudai International Symposium on [bi]*, 112-113, 2006
353. Masaki Nomura, Toshio Aoyagi, Stability of Synchronous Solutions in Weakly Coupled Neuron Networks. *Progress of Theoretical Physics*, 113, 911-925, 2005
354. Takashi Takekawa, Toshio Aoyagi, Tomoki Fukui, Synchronization properties on slow oscillatory activity in a cortex network model. *Progress of Theoretical Physics Supplement*, S161, 356-359, 2006
355. Masaki Nomura, Takuma Tanaka, Takeshi Kaneko, Toshio Aoyagi, Phase analysis of inhibitory neurons involved in the thalamocortical loop. *Progress of Theoretical Physics Supplement*, S161, 310-313, 2006
356. Takaki Araki, Toshio Aoyagi, A Possible Role of Incoming Spike Synapses in Associative Memory Model with STDP

- Learning rule, International Symposium on Oscillation, Progress of Theoretical Physics Supplement, S161, 152-155, 2006
357. Takasaki Aoki, Toshio Aoyagi, Synchrony-induced switching behavior of spike-pattern attractors created by spike-timing dependent plasticity, *Neural Computation*, (in press).
358. Takasaki Aoki, Toshio Aoyagi, Self-Organizing maps with Asymmetric Neighborhood function, *Neural Computation*, (in press).
359. Masaki Nomura, Toshio Aoyagi, Stability Analysis of Synchronous and Asynchronous Behavior in Periodically Spiking Neurons, *The First International Conference on Complex Medical Engineering-CME2006*, OS06.4, CD-ROM, 2005
360. Y. Tanii, J. Nishi, Optimality of the minimum endpoint variance model based on energy consumption, *Brain-inspired IT II: Decision and Behavioral Choice Organized by Natural and Artificial Brains*, 1291, 101-104, 2006
361. Takeuchi, H., Paul, R. K., Matsuzaka, E., and Kubo, T., EcR-A expression in the brain and ovary of the honeybee, *Zool. Sci.*, in press, 2007
362. Uno, Y., Fujiyuki, T., Takeuchi, H., Morioka, M., and Kubo, T., Identification of proteins whose expression is up- or down-regulated in the mushroom bodies in the honeybee brain using proteomics, *FEBS Lett.*, 581, 197-101, 2007
363. Hideaki Takeuchi, Gene expression in the Honeybee Brain Mushroom Body and its Gene Orthologues. *Evolution of Nervous Systems (Elsevier)*, 1, 457-469, 2006
364. Fujiyuki, T., Ohka, S., Takeuchi, H., Ono, M., Nomoto, A., and Kubo, T., Prevalence and phylogeny of Kakugo virus, a novel insect piorna-like virus that infects the honeybee (*Apis mellifera* L.) under various colony conditions, *J. Virol.*, 80, 23, 11528-11538, 2006
365. Paul, R. K., Takeuchi, H. and Kubo, T., Expression of two ecdysteroid-regulated genes, Broad-Complex and E75, in the brain and ovary of the honeybee (*Apis mellifera* L.), *Zool. Sci.*, 23, 12, 1085-1092, 2006
366. Kameda, T., Fujiyuki, T., Kucharski, R., Foret, S., Arment, S. A., Toth, A. L., Ohashi, K., Takeuchi, H., Kamikouchi, A., Kage, E., Morioka, M., Beyre, M., Kubo, T., Robinson, G. E., Maleszka, R., Carbohydrate metabolism genes and pathways in insects: insights from the honey bee genome. *Insect Mol. Biol.*, 15, 5, 563-576, 2006
367. Yamazaki, Y., Shirai, K., Paul, R. K., Fujiyuki, T., Wakamoto, A., Takeuchi, H. and Kubo, T., Differential expression of HR38 in the mushroom bodies of the honeybee brain depends on the caste and division of labor. *FEBS Lett.*, 580, 11, 2667-2770, 2006
368. Hori, S., Takeuchi, H., Arikawa, K., Kinoshita, M., Ichikawa, N., Sasaki, M., and Kubo, T., Associative visual learning, color discrimination, and chromatic adaptation in the harnessed honeybee *Apis mellifera* L. *J. Comp. Physiol. A*, 192, 7, 691-700, 2006
369. Lehman, H. K., Schulz, D. J., Barron, A. B., S. A., Wraight, L., Hardison, C., Whitney, S., Takeuchi, H., Paul, R. K., and Robinson, G. E., Division of labor in the honey bee (*Apis mellifera*): The role of tyramine beta-hydroxylase. *J. Exp. Biol.*, 209, 14, 2774-2784, 2006
370. Yasuaki Kuroe and Kei Mitsu, Generation of Oscillatory Trajectories with Specified Stability Degree Using Recurrent Neural Networks, *Proc. of International Joint Conference on Neural Networks*, 6510-6517, 2006
371. Yasuaki Kuroe and Yuriko Taniguchi, Models of Self-Correlation Type Complex-Valued Associative Memories and Their Performance Comparison, *Proc. of International Joint Conference on Neural Networks*, 605-609, 2006
372. Yasuaki Kuroe and Hitoshi Imai, A Learning Method for Synthesizing Spiking Neural Oscillators, *Proc. of International Joint Conference on Neural Networks*, 7613-7617, 2006
373. Yoshihiro Mori, Yasuaki Kuroe and Takehiro Mori, "A Synthesis Method of Gene Networks Based on Gene Expression by Network Learning, *Proc. of SICE-ICASE International Joint Conference*, 4545-4550, 2006
374. Nishikawa I., Iritani T., Sakakibara K., and Kuroe Y., "Phase Synchronization in Phase Oscillators and Complex-Valued Neural Networks and its Application to Traffic Flow Control", *Progress of Theoretical Physics Supplement*, 161, "302-305", 2006
375. "Nishikawa I., Iritani T., and Sakakibara K., "Improvements of the Traffic Signal Control by Complex-valued Neural Networks", *Proceedings of IEEE World Congress on Computational Intelligence 2006*, "1186-1191", 2006
376. Nishikawa I., Sakamoto H., Nouno I., Iritani T., Sakakibara K. and Ito, M., "Prediction of the O-glycosylation sites in Protein by Layered Neural Networks and Support Vector Machines", *Lecture Notes in Artificial Intelligence 4252, Part II*, "953-960", 2006
377. Nouno I., Sakamoto, H., Iritani, T., Sakakibara, K., Nishikawa, I. and Ito, M., "Prediction of Mucin-type O-glycosylation by Layered Neural Networks and Support Vector Machines", *Proceedings of the 17th International Conference on Genome Informatics 2006*, P111\_1-2, 2006
378. Sakakibara K., Noishiki M., Watanabe S., Tamaki H. and Nishikawa I., "Hierarchical Approach with Informational Feedback for Pickup and Delivery Problems", *Proceedings of the International Symposium on Scheduling 2006*, 48-53, 2006
379. Khoa N. L. D., Noishiki M., Sakakibara K., and Nishikawa I., "Stock Price Forecasting using Neural Networks with Inputs selected by Genetic Algorithm", *Proceedings of the 5th International Conference on Research, Innovation and Vision for the Future*, 2007
380. Khoa, N. L. D., Sakakibara, K., Nishikawa, I., "Stock price forecasting using back propagation neural networks with time and profit based adjusted weight factors, *Proceedings of SICE-ICASE 2006*, 5484-5488, 2006
381. "Noishiki M., Sakakibara K., Nishikawa I., Tamaki H. and Nakayama K.", "Autonomous Distributed Genetic Approach for Route Planning Problems", *Proceedings of SICE-ICASE 2006*, 6075-6079, 2006
382. Sakakibara K., Noishiki M., Tamaki H. and Nishikawa I., "A Study on Distributed Meta-Heuristic Approach for Route Planning", *Proceedings of SICE-ICASE 2006*, 4977-4980, 2006
- 2007
383. Ito, M.\* and Yano, M., Sinusoidal modeling for nonstationary voiced speech based on a local vector transform, *The Journal of the Acoustical Society of America*, 121, 3, 1731-1741, 2007
384. Nozomi Tomita\*, Masafumi Yano, Bipedal Robot Controlled by the Basal Ganglia and Brainstem Systems
385. Adjusting to Indefinite Environment, *Proc. of 2007 IEEE/ICME International Conference on Complex Medical Engineering*, 116-121, 2007
386. Yuki Yoshizawa\*, Nozomi Tomita, Yoshinari Makino, and Masafumi Yano, Control of Voluntary Movement in Indefinite Environment- Real-time Optimization of Reaching Patterns by Constraints Emergence and Satisfaction - *Proc. of 2007 IEEE/ICME International Conference on Complex Medical Engineering*, 107-110, 2007
387. Tomita, N.\*, Asano, T., Makino, Y. and Yano, M., Real-time and Distributed Autonomous Control of 2-joints Arm with Biarticular Muscles, *Proceedings of the 3rd International Symposium on Measurement, Analysis and Modeling of Human Functions*, 39-46, 2007
388. Y. Yoshizawa\*, N. Tomita, Y. Makino, and M. Yano, Autonomous Control of Reaching Movement by Mobility Measure, *International Journal of Robotics and Mechatronics*, 19, 4, 448-458, 2007
389. Y. Yoshizawa\*, N. Tomita, Y. Makino, M. Yano, Autonomous Decentralized Control of Redundant Arm in 3D Space by Mobility Measure, *2nd International Symposium on Mobiligence*, 81-84, 2007
390. M. Yano\*, Y. Yoshizawa, N. Tomita, Y. Makino, Voluntary Movements Controlled by Mi-Nashi Created in the Motor Cortices, *2nd International Symposium on Mobiligence*, 22-25, 2007
391. Ito, M.\* and Yano, M., Articulatory feature estimation for nonstationary vowels based on a local vector coding, *19th international congress on acoustics (Madrid)*, CAS-03-005, 2007
392. Matsumoto, J., Makino, Y., Miura, H. and Yano, M., Hippocampal model for spatial learning by using reward related cells, *Proceedings of Neuro2007 (The 30th Annual Meeting of the Japan Neuroscience Society)*, OIP-G02, 2007
393. Makino Y., Yasuake M., Naka Y., Miura H., Yano M., Olfactory computation using spatiotemporal pattern of network activity for odor representation, *NEUROSCIENCE RESEARCH (The 30th Annual Meeting of the Japan Neuroscience Society)*, S8S103-S103, 2007
394. Masakatsu Tsukamoto, Toshiyuki Kondo and Koji Ito, A Prosthetic Hand Control based on Nonstationary EMG at the Start of Movement, *Jr. of Robotics and Mechatronics*, 19, 4, 381-387, 2007
395. Koji Ito, Makoto Doi, Toshiyuki Kondo, Feed-forward Adaptation to a Varying Dynamical Environment during Reaching Movements, *Jr. of Robotics and Mechatronics*, 19, 4, 395-401, 2007
396. Toshiyuki Kondo and Koji Ito, An Environment Cognition and Motor Adaptation Model by Eliciting Sensorimotor Constraints based on Time-series Observations, *Jr. of Robotics and Mechatronics*, 19, 4, 395-401, 2007
397. Toshiyuki Kondo, Evolutionary design and behavior analysis of neuromodulatory neural networks for mobile robot control, *Applied Soft Computing*, 7, 189-202, 2007
398. Toshiyuki Kondo, Koji Ito, An Intrinsic Neuromodulation Model for Realizing Anticipatory Behavior in Reaching Movement under Unexperienced Force Fields, in M.V. Butz et al. (eds): *Anticipatory Behavior in Adaptive Learning Systems: Advances in Anticipatory Processing*, Springer, 4520, 254-266, 2007
399. J.L. Wu, K.Ito, S. Tobimatsu, T. Nishida, F. Fukuyama, *Complex Medical Engineering*, Springer, 2007
400. Manabu Gouko, Naoki Tomi, Tomoaki Nagano and Koji Ito, Self-Organized Learning Model for behavior emergence and its application to mobile robot, *Proceedings of The 3rd International Symposium on Communications, Control and Signal Processing (ISCCSP2008)*, in press, 2008
401. Koji Ito, Masakatsu Tsukamoto and Toshiyuki Kondo, Discrimination of Intended Movements based on Nonstationary EMG for A Prosthetic Hand Control, *Proceedings of The 3rd International Symposium on Communications, Control and Signal Processing (ISCCSP2008)*, in press, 2008
402. Tomoaki Nagano, Manabu Gouko and Koji Ito, Distributed Motor Control System With Transmission Time Delay, *Proceedings of The 3rd International Symposium on Communications, Control and Signal Processing (ISCCSP2008)*, in press, 2008
403. Manabu Gouko, Naoki Tomi, Tomoaki Nagano and Koji Ito, Behavior emergence model for performing multiple tasks, *Proceedings of 2008 IEEE International Conference on Distributed Human-Machine Systems (DHMS2008)*, in press, 2008
404. Tomoaki Nagano, Manabu Gouko and Koji Ito, A 3-dimensional Distributed Motor Control System With Transmission Time Delay, *Proceedings of 2008 IEEE International Conference on Distributed Human-Machine Systems (DHMS2008)*, in press, 2008
405. Takeshi Sakurada, Hiroaki Gomi, Koji Ito, Implicit interaction between bimanual cyclic finger movements examined by kinematic and force field adaptation tests, *SIN Final Program*, 56, 2007
406. Takayuki Nozawa, Toshiyuki Kondo, Lattice Molecular Automata with Reversibility, *2nd International Workshop on Natural Computing*, 2007
407. Manabu Gouko, Koji Ito, An Action Generation Model Using Time Series Prediction, *Proceedings of International Joint Conferences on Neural Networks 2007*, 602-607, 2007
408. Naoki Tomi, Manabu Gouko, Koji Ito, Toshiyuki Kondo, Decomposition of Internal Models in Arm Movements under Mixed Force, *Proceedings of The second International Symposium on Mobiligence*, 69-72, 2007
409. Manabu Gouko, Koji Ito, A predictive models selection model for an action generation, *Proceedings of The second International Symposium on Mobiligence*, 65-68, 2007
410. Koji Ito, Toshiyuki Kondo, Feedforward Adaptation to a varying dynamical environment in arm movements, *Proceedings of The second International Symposium on Mobiligence*, 26-29, 2007
411. Toshiyuki Kondo, Yuya Kobayashi, Simultaneous Learning of a Mouse Operation with Conflicting Rotational Transformations, *Proceedings of 2nd International Symposium on Mobiligence*, 73-76, 2007
412. Naoki Tomi, Manabu Gouko, Koji Ito, Toshiyuki Kondo, Decomposition of Internal Models in Arm Reaching Motions under Mixed Dynamic Environments, *Proceedings of The 3rd International Symposium on Measurement, Analysis, and Modeling of Human Functions (ISHF2007)*, 55-60, 2007
413. Takeshi Sakurada, Hiroaki Gomi, Jun Izawa, Koji Ito, Bimanual finger control mechanism related to the force field and visual adaptation, *Proceedings of The 3rd International Symposium on Measurement, Analysis, and Modeling of Human Functions (ISHF2007)*, 47-54, 2007
414. Mitsuru Takahashi, Manabu Gouko, Koji Ito, Toshiyuki Kondo, Reconstruction of Motor Function by Combining Electroencephalogram (EEG) with Functional Electrical Stimulation (FES), *Proceedings of The 3rd International Symposium on Measurement, Analysis, and Modeling of Human Functions (ISHF2007)*, 67-73, 2007
415. Koji Ito, Mobiligence: Adaptive Motor Behaviors in Dynamic Environments, *Proceedings of The 3rd International Symposium on Measurement, Analysis, and Modeling of Human Functions (ISHF2007)*, 11-16, 2007
416. \*Toshiyuki Kondo, Yuya Kobayashi, Simultaneous Learning of Computer Mouse Operation with Conflicting Rotational Transformations, *The Third International Symposium on Measurement, Proceedings of 3rd International Symposium on Measurement Analysis and Modeling of Human Functions (ISHF2007)*, 55-60, 2007
417. Koji Ito, Makoto Doi, Toshiyuki Kondo, Feedforward Adaptation to Stable and Unstable Dynamics in Arm Movements, *Proceedings of 15th Mediterranean Conference on Control and Automation (MED2007)*, 1-6, 2007
418. K. Takakusaki, R. Ohta, H. Harada, Modulation of the excitability of hindlimb motoneurons by the basal ganglia efferents to the brainstem in decerebrate cats. *2nd Mobiligence International Symposium in Awaji*, 2007, 161-165, 2007
419. R. Ohta, R. K. Takakusaki, H. Harada, S. Nonaka, Y. Harabuchi, Contribution of GABAergic receptors on neurons in the lateral lemniscus to the control of swallowing in decerebrate cats, *2nd Mobiligence International Symposium in Awaji*, 2007, 170-174, 2007
420. Y. Koyama, K. Takahashi, T. Kodama, K. Takakusaki, Hypothalamic regulation of muscular tone - Involvement of orexinergic and GABAergic neurons, *2nd Mobiligence International Symposium in Awaji*, 2007, 166-169, 2007
421. K. Takakusaki, R. Ohta, H. Harada, Modulation of the excitability of hindlimb motoneurons during fictive locomotion by the basal ganglia efferents to the brainstem in decerebrate cats. *37th Annual Meeting of Society for Neuroscience, San-Diego, CA, USA, 2007*, 2007
422. R. Ohta, R. K. Takakusaki, H. Harada, S. Nonaka, Y. Harabuchi, Contribution of GABAergic receptors on neurons in the lateral lemniscus to the control of swallowing in decerebrate cats. *37th Annual Meeting of Society for Neuroscience, San-Diego, CA, USA, 2007*, 2007
423. K. Takakusaki, Forebrain control of locomotion, Japan - Italy International Seminar Scientific Program "Motor Adaptation / Learning Analysis and Its Application to Neuro-Rehabilitation", Tokyo, JAPAN, 2007
424. K. Takakusaki, Role of cholinergic projections from the pedunculopontine tegmental nucleus (PPN), *International NSCC workshop*, Tokyo, JAPAN, 2007
425. K. Yoshimi, A. Suzuki, G. Oyama, M. Kagohashi, N. Hattori, T. Nakazato, Y. Einaga, S. Kitazawa, Diamond microelectrodes for in vivo dopamine detection, *37th Annual Meeting of Society for Neuroscience (SfN) San Diego*, 2007
426. A. Suzuki, T. Ivandini, A. K. Yoshimi, A. Fujishima, G. Oyama, T. Nakazato, N. Hattori, S. Kitazawa, Y. Einaga, Fabrication of Boron-Doped Diamond Microelectrodes for in vivo Analysis of Dopamine, *Material Research Society (Boston, MA)*, 2007
427. B. Bloem, I. Toni, F. Mori and J. Nielsen, Functional imaging of axial motor control, *International Society of Posture and Gait Research*, 2007
428. F. Mori and K. Nakajima, Adaptive locomotor control in bipedal walking monkey, *SICE Annual Conference*, 2007
429. K. Nakajima, F. Mori, A. Murata, M. Inase, Neuronal Activity in Cortical Motor Areas of an Unrestrained Japanese Monkey Walking on a Treadmill, *The 2nd International Symposium on Mobiligence*, 35-38, 2007
430. K. Nakajima, F. Mori, A. Murata, M. Inase, Neuronal Activity in Cortical Motor Areas of an Unrestrained Japanese Monkey Walking on a Treadmill, *The 2nd International Symposium on Mobiligence*, 35-38, 2007
431. K. Takakusaki, What are substrates for normal and abnormal gait?, *16th International Parkinson Disease Treatment Symposium*, Tokyo, JAPAN, 2007, 2007
432. K. Takakusaki, Forebrain control of locomotor behaviors, *Brain Research Review*, 57, 192-198, 2008
433. H. Yamada, S. Tanno, K. Takakusaki, Tolonium, Intracastical injection of orexin-A prevents ethanol-induced gastric mucosal damage in rats, *Journal of Gastroenterology*, 42, 336-341, 2007
434. K. Takakusaki, What are substrates for normal and abnormal gait?, *Journal of Neurology (in press)*,
435. M. Adachi, S. Nonaka, A. Kanata, T. Arakawa, R. Ota, H. Harada, K. Takakusaki, Y. Harabuchi, Carbachol injection into the pontine reticular formation depresses laryngeal muscle activity and airway reflexes in decerebrate cats, *Neuroscience Research (in press)*,
436. K. Takakusaki, Basal ganglia modulation of fictive locomotion in decerebrate cats, *Neuroscience Research (Suppl)*, S8S34, 2007
437. N. Kamiyama, H. Matsui, K. Takakusaki, M. Kashiwayanagi, Insulin-like growth factor-1 and 2-aminoethoxydiphenyl borate induce extracellular calcium influx in mouse olfactory sensory neurons, *Journal of Physiological Science (Suppl)*, S7, S98, 2007
438. M. Kagohashi, T. Nakazato, K. Yoshimi, S. Moizumi, N. Hattori, S. Kitazawa, Wireless voltammetry recording in unanesthetized behaving rats, *Neuroscience Research*, 60, 1, 120-127, 2008
439. T. Nakazato, M. Kagohashi, K. Yoshimi, Influence of pH on voltammetric measurement of dopamine, *Biogenic Amines*, 20, 1-23-30, 2006
440. A. Suzuki, A. T. Ivandini, K. Yoshimi, A. Fujishima, G. Oyama, T. Nakazato, N. Hattori, S. Kitazawa, Y. Einaga, Fabrication, Characterization, and Application of Boron-Doped Diamond Microelectrodes for in Vivo Dopamine Detection, *Analytical Chemistry*, 79, 22, 8608-8615, 2007
441. S. Ohmae, X. Lu, Y. Uchida, T. Takahashi, S. Kitazawa, Neuronal activity related to anticipated and elapsed time in macaque supplementary eye field, *Experimental Brain Research*, 184(4):593-8, 2008
442. Y. Uchida, X. Lu, S. Ohmae, T. Takahashi, S. Kitazawa, Neural activity related to reward size and rewarded target position in primate supplementary eye field, *Journal of Neuroscience*, 27, 50, 13750-13755, 2007
443. S. Kitazawa, S. Moizumi, A. Okuzumi, F. Saito, S. Shibuya, T. Takahashi, M. Wada, S. Yamamoto, Reversal of subjective temporal order due to sensory and motor integrations, *In: Attention Perform edited by Haggard P, Kawato M, and Rossetti Y. Oxford Univ Press*, 73-97, 2007

444. S. Moizumi, S. Yamamoto, S. Kitazawa, Referral of tactile stimuli to action points in virtual reality with reaction force. *Neuroscience Research*, 59,1,60-67,2007
445. K. Yamamoto, M. Kawato, S. Kotosaka, S. Kitazawa, Encoding of movement dynamics by Purkinje cell simple spike activity during fast arm movements under resistive and assistive force fields. *Journal of Neurophysiology*, 97,2,1588-1599,2007
446. S. Shibuya, T. Takahashi, S. Kitazawa, Effects of visual stimuli on temporal order judgments of unimanual finger stimuli. *Experimental Brain Research*, 179,701-709,2007
447. Shinya Aoi, Yuki Sato, Kazuo Tsuchiya, Investigation of the Effects on Stability of Foot Rolling Motion Based on a Simple Walking Model. *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2007)*, 2987-2992,2007
448. Oghara, N., Aoi, S., Sugimoto, Y., Nakatsukasa, M., Tsuchiya, K., System biomechanics study of locomotion in the Japanese monkey. *The 2nd International Symposium on Mobilitence*, 41-44,2007
449. Oghara, N., Aoi, S., Sugimoto, Y., Nakatsukasa, M., Tsuchiya, K., A constructive simulation study of locomotion in the Japanese monkey based on a neuro-musculoskeletal model. *International Workshop on Mobilitence*, 2007
450. S. Aoi, K. Tsuchiya, Adaptive Behavior in Turning of an Oscillator-driven Biped Robot. *Autonomous Robots*, 23,1,57-57,2007
451. N. Oghara, E. Hirasaki, H. Kumakura, M. Nakatsukasa, Ground-reaction-force profiles of bipedal walking in bipedally trained Japanese monkeys. *Journal of Human Evolution*, 53,302-308,2007
452. Kagaya, M., Oghara, N., Nakatsukasa, M., Morphological study of the anthropoid thoracic cage: scaling of thoracic width and analysis of rib curvature. *Primates*, in press
453. Y. Sugimoto, S. Aoi, N. Oghara, K. Tsuchiya, The Stabilizing Function of Musculoskeletal System for Periodic Motion. *2nd International Symposium on Mobilitence*, 2007
454. Y. Sugimoto, K. Osuka, Hierarchical Implicit Feedback Structure in Passive Dynamic Walking. *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2007
455. Takashi Takuma and Koh Hosoda, Utilizing Joint Compliance for Controlling Walking Velocity of the Passive Dynamic Walker. *2nd International Symposium on Mobilitence*, 2007
456. Takashi Takuma and Koh Hosoda, Controlling Walking Behavior of Passive Dynamic Walker utilizing Passive Joint Compliance. *IEEE/RSJ 2007 International Conference on Intelligent Robots and Systems*, 2975-2980,2007
457. Zu Guang Zhang, Toshiki Masuda, Hiroshi Kimura and Kunikatsu Takase, Towards Realization of Adaptive Running of a Quadruped Robot Using Delayed Feedback Control. *IEEE Robotics and Automation*, 43,25-43,30,2007
458. Christophe Mauffroy, Hiroshi Kimura and Kunikatsu Takase, Biologically Inspired Neural Controller for Quadruped. *IEEE Robotics and Biomimetics*, 12,12-12,17,2007
459. K.Inoue, T.Sumi, S.Ma, CPG-based Control of a Simulated Snake-like Robot. *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 1957-1962,2007
460. K.Inoue, T.Sumi, N.Sato, S.Ma, CPG-based Adaptable Control of a Snake-like Robot. *SICE Annual Conference 2007*, 2161-2164,2007
461. Takashi Takuma and Koh Hosoda, Terrain Negotiation of a Compliant Biped Robot Driven by Antagonistic Artificial Muscles. *Journal of Robotics and mechatronics*, 19,4,423-428,2007
462. Koh Hosoda and Takashi Takuma and Aitsuki Nakamoto and Shinji Hayashi, Biped Robot Design Powered by Antagonistic Pneumatic Actuators for Multi-Modal Locomotion. *Robotics and Autonomous Systems*, 56,1,46-53,2008
463. Hiroshi Kimura, Chris Mauffroy and Toshiki Masuda, Emergence of Quadrupedal Gaits as Interaction among the Brain, Body and Environment. *2nd International Symposium on Mobilitence*, 113-116,2007
464. Chris Mauffroy and Hiroshi Kimura, Towards a General Neural Controller for Quadrupedal Locomotion. *2nd International Symposium on Mobilitence*, 117-120,2007
465. Yuji Ootada and Hiroshi Kimura, Bipedal Walking Using Natural Dynamics and Delayed Stepping Reflex. *2nd International Symposium on Mobilitence*, 121-124,2007
466. Toshiki Masuda and Hiroshi Kimura, Realization of Adaptive Running of a Quadruped Robot Using Delayed Feedback Control and Phase Resetting. *2nd International Symposium on Mobilitence*, 125-128,2007
467. Yuji Ootada, Hiroshi Kimura and Kunikatsu Takase, Efficient Bipedal Walking Using Delayed Stepping Reflex. *SICE Annual Conference 2007*, 2170-2174,2007
468. K.Tsujita, T.Inoura and T.Masuda, Development of Oscillator-controlled Biped Walker with Pneumatic Actuator. *Proc. of Int. Symp. on Mobilitence*, 129-132,2007
469. K.Tsujita, T.Inoura and T.Masuda, Oscillator-controlled Bipedal Walker with Pneumatic Actuators. *Proc. of SICE Annual Conference 2007*, 2165-2169,2007
470. K.Tsujita, T.Inoura, T.Kobayashi and T.Masuda, Adaptive locomotion control of a legged robot with pneumatic actuators. *Proc. of Int. Conf. on Robotics and Biomimetics 2007*, 1218-1223,2007
471. Hiroshi Kimura, Yasuhiro Fukuoka and Avis H. Cohen, Adaptive Dynamic Walking of a Quadruped Robot on Natural Ground Based on Biological Concepts. *Int. Journal of Robotics Research*, 26,5,475-490,2007
472. K.Tsujita and T.Masuda, Simulation Study on Acquisition Process of Locomotion by using an Infant Robot. *International Journal of Advanced Robotics Systems*, 4,09-422,2007
473. K.Tsujita, A.Morioka, K.Nakani, K.Suzuki and T.Masuda, Oscillator-controlled Bipedal Walk with Pneumatic Actuators. *International Journal of Mechanical Science and Technology*, 21,976-980,2007
474. M. Sakura, A. Yoritsune, M. Ashikaga and H. Aonuma, Fighting experiences modulate aggressive and avoidance behaviors in crickets against male cuticular substances. *Proceeding of the 2nd International Symposium on Mobilitence*, 2,243-246,2007
475. M. Ashikaga, M. Kikuchi, T. Hiraguchi, M. Sakura, H. Aonuma and J. Ota, Modeling of socially adaptive behavior in crickets. *Proceeding of the 2nd International Symposium on Mobilitence*, 2,2007
476. H. Aonuma, M. Sakura, M. Kikuchi, T. Hiraguchi, M. Ashikaga, J. Ota, K. Kawabata, T. Fujiki, Y. Ikemoto and H. Asama, Social experience dependent behavior selection in the cricket - from neuroethological approach to modeling - *Proceeding of the 2nd International Symposium on Mobilitence*, 2,2007
477. M. Kikuchi and H. Aonuma, Distributions of aminergic and nitric oxidergic neurons. *Proceeding of the 2nd International Symposium on Mobilitence*, 2,2007
478. A.Yoritsune and H. Aonuma, 3-D atlas of the cricket antennal lobe. *Proceeding of the 2nd International Symposium on Mobilitence*, 2,2007
479. K. Kawabata, T. Fujiki, M. Ashikaga, J. Ota, H. Aonuma and H. Asama, A study on neural circuit model of insects for adaptive behavior selection - Verification of action selection model in multi-individual environments - *Proceeding of the 2nd International Symposium on Mobilitence*, 2,2007
480. E. Tsuji, H. Aonuma, F. Yokohari and N. Nishikawa, Serotonin-immunoreactive Neurons in the Antennal Sensory System of the Brain in the Carpenter Ant, *Camponotus japonicus*. *Zool. Sci.*, 24,836-849,2007
481. D. Hatakeyama, H. Aonuma, E. Ito and K. Elkes, Localization of glutamate-like immunoreactive neurons in the central and peripheral nervous system. *The Biological Bulletin*, 213,172-186,2007
482. M. Iwasaki, I. Nishino, D. Antonia and H. Aonuma, Effects of NO/cGMP signaling on the behavioral change in subordinate male crickets, *Gryllus bimaculatus*. *Zool. Sci.*, 24,860-868,2007
483. M. Ashikaga, M. Kikuchi, T. Hiraguchi, M. Sakura, H. Aonuma and J. Ota, Foraging task of multiple mobile robots in a dynamic environment using adaptive behavior in crickets. *Journal of Robotics and Mechatronics*, 19,4,446-473,2007
484. K. Kawabata, T. Fujiki, Y. Ikemoto, H. Aonuma and H. Asama, A neuromodulation model for adaptive behavior selection of the cricket. *Journal of Robotics and Mechatronics*, 19,4,388-394,2007
485. M. Sakura, T. Hiraguchi, K. Ohkawara and H. Aonuma, The compartment structures of the antennal lobe in the ant *Aphaenogaster smithesi japonica*. *Acta Biol Hungarica*, accepted, 2008
486. R. Okada, H. Ikeno, N. Sasayama, H. Aonuma, D. Kurabayashi and E. Ito, The dance of the honeybee: how do honeybees dance to transfer food information effectively?. *Acta Biol Hungarica*, accepted, 2008
487. D. Kurabayashi, H. Aonuma, T. Funato, T. Fujiki, M. Ashikaga, J. Ota and H. Asama, Artificial model for behavior switching by using network transition through neuromodulation effect. *Comp. Biochem. Physiol.*, 148A, S32,2007
488. H. Aonuma, NO/cGMP system and biogenic amine system in antagonistic behavior in the cricket. *Comp. Biochem. Physiol.*, 148A, S33,2007
489. Kanzaki R, Insect-machine hybrid systems - novel neuroethological approaches for analyzing adaptive behaviors. *The 4th Asia-Pacific Conference on Chemical Ecology*, 2007
490. Kanzaki R, Insect-Machine Hybrid System for Evaluating an Adaptive Behavior. *Comparative Biochemistry and Physiology*, 148A, Suppl. 1, S32,2007
491. Sakurai T, Uchino K, Sezutsu H, Tamura T and Kanzaki R, Molecular and neural bases of pheromone discrimination in the silkworm, *Bombyx mori*. *Comparative Biochemistry and Physiology*, 148A, Suppl. 1, S80,2007
492. Kanzaki R, How does the Insect-Microbrain Generate Adaptive Behavior?. *The 3rd Yamada Symposium on From Chaos to Cosmos: Integration in Biological Systems*, 2007
493. Kanzaki R, Insect-Machine Hybrid System for Evaluating and Understanding an Adaptive Behavior. *IEEE International Conference on Robotics and Biomimetics*, 2007
494. Wang H, Ando N and Kanzaki R, The steering control of free flight maneuvers in *Agrius*. *Comparative Biochemistry and Physiology*, 146,4, Suppl. 1, S114-S115,2007
495. Ando N, Yamashita A, Matsura W, Takahashi H and Kanzaki R, Visual and odor integration for high efficacy of odor searching tasks based on the silkworm. *Proceedings of the 2nd International Symposium on Mobilitence*, 227-230,2007
496. Minegishi R, Torihara S, Kurabayashi D and Kanzaki R, Construction of a bio-machine fusion system using brain information that commands an insect's behavior. *Proceedings of the 2nd International Symposium on Mobilitence*, 235-238,2007
497. Emoto S, Ando N, Takahashi H and Kanzaki R, Behavioral responses to unintentional body movements in insects analyzed by an insect-controlled robot. *Proceedings of the 2nd International Symposium on Mobilitence*, 231-234,2007
498. Kanzaki R, Emoto S, Minegishi R, Torihara S, Kurabayashi D and Takahashi H, Insect-machine hybrid systems - novel neuroethological approaches for analyzing adaptive behaviors. *Abstract of the 8th Congress of the International Society for Neuroethology*, 253,2007
499. Fukushima R and Kanzaki R, Anatomical organization of Kenyon cells in the mushroom body of the silkworm moth, *Bombyx mori*. *Abstract of the 8th Congress of the International Society for Neuroethology*, 70,2007
500. Ando N, Wang H, Kanzaki R, Flight control of a freely flying hawkmoth flight muscle activities and wing kinematics. *Abstract of the 8th Congress of the International Society for Neuroethology*, 167,2007
501. Sakurai T, Yamagata T, Uchino K, Sezutsu H, Tamura T and Kanzaki R, Molecular cloning and expression pattern of ekb-like genes from silkworm, *Bombyx mori*. *Comparative Biochemistry and Physiology*, 148A, Suppl. 1, S10,2007
502. Sakurai T, Uchino K, Sezutsu H, Tamura T and Kanzaki R, Axonal projections of pheromone receptor neurons to the antennal lobe macroglomerular complex in the silkworm, *Bombyx mori*. *The 4th Asia-Pacific Conference on Chemical Ecology*, 2007
503. Shuzo M, Okada K, Kanzaki R and Shimoyama I, Fluorescence detection system using metal-coated glass micropipette. *20th International Conference on Micro Electro Mechanical Systems*, 207-210,2007
504. K. Ishiura, Y. Satoji, H. Aonuma and O. Mamiya, The 4th Asia-Pacific Conference on Chemical Ecology, 2007
505. M. Sakura, T. Hiraguchi, K. Ohkawara and H. Aonuma, Distribution of neuromodulators in the olfactory center of the ant *Aphaenogaster smithesi japonica*. *The 11th ISIN Symposium on the Neurobiology of Invertebrates*, 2007
506. R. Okada, H. Ikeno, N. Sasayama, H. Aonuma, D. Kurabayashi and E. Ito, The dance of the honeybee: how do they dance to transfer the food information effectively?. *The 11th ISIN Symposium on the Neurobiology of Invertebrates*, 2007
507. Ikono H, Nishikawa T, Hachida T, Kanzaki S, Seki Y, Ohzawa I and Usui S, Development and application of CMS based database modules for neuroinformatics. *Neurocomputing*, 70,2122-2128,2007
508. Emoto S, Ando N, Takahashi H and Kanzaki R, Insect-Controlled Robot - Evaluation of Adaptation Ability - *Journal of Robotics and Mechatronics*, 19,4,436-443,2007
509. Seki Y and Kanzaki R, Morphological classification of antennal lobe local interneurons in *Bombyx mori* by the intracellular staining under visual control method. *Journal of Comparative Neurology*, 506,93-107,2007
510. Iwano M, Hill E, Mori A, Mishima T, Kumagai T, Ito K and Kanzaki R, Generation mechanism of flip-flop activity in the lateral accessory lobe and ventral protocerebrum of the insect brain. *Journal of Comparative Neurology*, accepted, 2007
511. Kanzaki R, How does a microbrain generate adaptive behavior?. *Congress Series 1301 Brain-Inspired IT III*, 2007
512. Wang H, Ando N and Kanzaki R, Active control of free flight manoeuvres in a hawkmoth, *Agrius convolvuli*. *Journal of Experimental Biology*, 211,409-422,2008
513. K. Kawabata, T. Fujiki, Y. Ikemoto, H. Aonuma, H. Asama, A Neuromodulation Model for Adaptive Behavior Selection by the Cricket. *Nitric Oxide (NO)/Cyclic Guanosine MonoPhosphate (cGMP) Cascade Model*. *Journal of Robotics and Mechatronics*, 19,4,388-394,2007
514. Y. Ikemoto, K. Kawabata, T. Miura, H. Asama, Mathematical Model of Proportion Control and Fluctuation Characteristic in Termite Caste. *Journal of Robotics and Mechatronics*, 19,4,429-435,2007
515. M. Otake, K. Arai, M. Kato, T. Maeda, Y. Ikemoto, K. Kawabata, T. Takagi, H. Asama, Experimental Analysis of the Attribution of Own Actions to the Intention of Self or Others by the Multiple Forward Models. *Journal of Robotics and Mechatronics*, 19,4,482-488,2007
516. Masatoshi Ashikaga, Mika Kikuchi, Tetsutaro Hiraguchi, Midori Sakura, Hitoshi Aonuma and Jun Ota, Foraging Task of Multiple Mobile Robots in a Dynamic Environment Using Adaptive Behavior in Crickets. *Journal of Robotics and Mechatronics*, 19,4,466-473,2007
517. K. Kawabata, T. Fujiki, M. Ashikaga, J. Ota, H. Aonuma, H. Asama, A Study on Neural Circuit Model of Insects for Adaptive Behavior Selection - Verification of Action Selection Model in Multi-individual Environments - *Proceedings of the 2nd International Symposium on Mobilitence*, 187-190,2007
518. H. Aonuma, M. Sakura, M. Kikuchi, T. Hiraguchi, M. Ashikaga, J. Ota, K. Kawabata, T. Fujiki, Y. Ikemoto, H. Asama, Social Experience Dependent Behavior Selection in the Cricket - from neuroethological approaches to modeling - *Proceedings of the 2nd International Symposium on Mobilitence*, 16-19,2007
519. Y. Ikemoto, T. Fujiki, K. Kawabata, H. Aonuma, T. Miura, H. Asama, Neural Modeling of Social Adaptive Behaviors of Insects. *Japan-Korea Joint Seminar on Information, Communications and Robotics Technologies for Dependable and Secure Societies*, 2007
520. Y. Ikemoto, K. Kawabata, T. Miura, H. Asama, Mathematical Model of Proportion Control in Termite Caste Differentiation. *Proceedings of the 2nd International Symposium on Mobilitence*, 195-198,2007
521. Masatoshi Ashikaga, Mika Kikuchi, Tetsutaro Hiraguchi, Midori Sakura, Hitoshi Aonuma and Jun Ota, Modeling of Socially Adaptive Behavior in Crickets. *Proceedings of the 2nd International Symposium on Mobilitence*, 191-194,2007
522. Yusuke Tamura, Masao Sugi, Jun Ota and Tamio Arai, Estimation of User's Intention Inherent in the Movements of Hand and Eyes for the Deskwork Support System. *Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 3709-3714,2007
523. Kenji Terabayashi, Natsuki Miyata, Makiko Kouchi, Masaaki Mochimaru and Jun Ota, Experience of Various Sized Hands: Visual Delay Effect. *Proceedings and Posters of 12th Int. Conf. HCI International 2007*, 1099-1013,2007
524. Kenji Terabayashi, Natsuki Miyata and Jun Ota, Grasp Strategy when Experiencing Hands of Various Size. *Proceedings of the 2007 IEEE International Conference on Robotics and Biomimetics*, 1422/1427,2007
525. Tetsuro Funato, Daisuke Kurabayashi, Masahito Nara, Hitoshi Aonuma, Development of a Structure-mediated Behavior Selector Using Oscillator Network. *Proc. IEEE Int. Conf. Robotics and Biomimetics*, 1206-1211,2007
526. Takaaki Shimono, Daisuke Kurabayashi, Kunio Okita, Tetsuro Funato, Implementation of Formation Transition System using synchronization among a Mobile Robot Group. *6th International Conference on Field and Service Robotics*, 303/312,2007
527. Daisuke Kurabayashi, Hitoshi Aonuma, Tetsuro Funato, Tomohisa Fujiki, Masatoshi Ashikaga, Jun Ota, Hajime Asama, Artificial model for behavior switching by using network transition through neuromodulation effect. *7th Int. Congress of Comparative Physiology and Biochemistry*, 2007
528. Tetsuro Funato, Daisuke Kurabayashi, Network Structure for Control of Coupled Multiple Non-Linear Oscillators. *IEEE Transactions on Systems, Man and Cybernetics - Part B in print*, 2008
529. Daisuke Kurabayashi, Tomohiro Inoue, Akira Yajima, Tetsuro Funato, Emergence of a small-world like communication network by local ad hoc negotiations. *Journal of Robotics and Mechatronics*, 19,4,459-465,2007
530. Daisuke Kurabayashi, Katsunori Urano, Tetsuro Funato, Emergent Transportation Networks by Considering Interactions between Agents and their Environment. *Advanced Robotics*, 21,12,1339-1349,2007
531. M. Inbe, \*K. Osuka, Design of the Passive Dynamic Walking Robot by Applying its Dynamic Properties. *Journal of Robotics and Mechatronics*, 19,4,402-408,2007
532. M. Inbe, \*K. Osuka, A Designing Method of the Passive Dynamic Walking Robot via Analogy with the Phase Locked Loop Circuits. *Bioinspiration and Robotics - Walking and Climbing Robots*, Eds.: M. K. Habib, 79-94,2007
533. \*K. Osuka, M. Inbe, Y. Sugimoto, On Passive Adaptive Mechanism in Passive Dynamic Walking. *Proceedings of the International Conference on Morphological Computation, session 27-2*, 2007
534. \*K. Osuka, M. Inbe, Y. Sugimoto, Adaptive Function Embedded in Passive Dynamic Walking. *Proceedings of the International WORKSHOP on MOBILIGENCE*, 2007
535. \*K. Osuka, On Passive Adaptive Mechanism in Passive Dynamic Walking. *Proceedings of the International Conference on Control, Automation and Systems 2007*, 2683-2686,2007
536. D. Owaki, \*A. Ishiguro, Mechanical Dynamics That Enables Stable Passive Dynamic Bipedal Running - Enhancing Self-stability by Exploiting Nonlinearity in the Leg - *Journal of Robotics and Mechatronics*, 19,4,374-380,2007
537. D. Owaki and \*A. Ishiguro, Mechanical Dynamics That Enables Stable Passive Dynamic Bipedal Running - Enhancing Self-stability by Exploiting Nonlinearity in the Leg - *Journal of Robotics and Mechatronics*, 19,4,374-380,2007
538. T. Umedachi, \*A. Ishiguro, Amoeboid Locomotion That Exploits Real-time Tunable Springs and Law of Conservation of Protoplasmic Mass. *Proc. of the 2nd International Symposium on Mobilitence*, 263-266,2007
539. D. Owaki, K. Osuka, \*A. Ishiguro, Stable Passive Dynamic Bipedal Running by Exploiting the Body Dynamics

- Properties,Proc.of the 2nd International Symposium on Mobilitence,259-262,2007
540. W. Watanabe, \*A. Ishiguro, Cheap Learning That Exploits Multiaxial Muscles: A Case Study with a 2D Serpentine Robot, Proc. of the 2nd International Symposium on Mobilitence, 267-270, 2007
541. M. Shimizu, K. Gohara, \*A. Ishiguro, Adaptive Amoeboid Locomotion Induced from Embodied Coupled Oscillators, Proc. of the 2nd International Symposium on Mobilitence, 271-274, 2007
542. \*A. Ishiguro, M. Shimizu, Amoeboid Locomotion Tells Us a Lot: A Collective Behavioral Approach to Mobilitence, Proc. of the 2nd International Symposium on Mobilitence, 52-55, 2007
543. W. Watanabe, \*A. Ishiguro, Improvement of Learning Efficiency by Exploiting Multiaxial Muscles — A Case Study with a 2D Serpentine Robot —, SICE 2007 PROCEEDINGS, 2155-2160, 2007
544. T. Umedachi, \*A. Ishiguro, Adaptive Amoeboid Locomotion That Exploits Law of Conservation of Protoplasmic Mass, SICE 2007 PROCEEDINGS, 2150-2154, 2007
545. Y. Yokokohji, T. Tsubouchi, A. Tanaka, T. Yoshida, E. Koyanagi, F. Matsumo, S. Hirose, H. Kuwahara, F. Takemura, T. Ino, K. Takita, N. Shiroma, T. Kamegawa, Y. Hada, \*X. Zheng, K. Osuka, T. Wataue, T. Kimura, H. Nakanishi, Y. Horiguchi, S. Tadokoro, and K. Ohno, Guidelines of Human Interface Design for Rescue Robots, Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2007
546. D. Owaki, Y. Matsumo, \*A. Ishiguro, Efficient and Adaptive Control of Walking Biped by Exploiting a Pulsed-CPG, 2007 IEEE/ICME International Conference on Complex Medical Engineering-CME2007, 111-115, 2007
547. M. Shimizu, \*A. Ishiguro, A Self-reconfigurable Robotic System That Exhibits Amoeboid Locomotion, Proc. of the 2007 IEEE/ICME International Conference on Complex Medical Engineering-CME2007, 101-106, 2007
548. Maro, T., Fujita, K., Shioiri, S., Matsumiya, K., & Kuriki, I. Implicit and explicit learning in visual search: the influence of eye movements, KEER2007 CD-ROM Proceedings, A17.1-A17.4, 2007
549. Nagata, H., Matsumiya, K., Shioiri, S., & Kuriki, I. Investigating the differences between explicit and implicit learning in a visuo-motor task, KEER2007 CD-ROM Proceedings, A14.1-A14.4, 2007
550. Shioiri, S., Iwada, Y., Tamai, N., Matsumiya, K., Yaguchi, H. The effect of attention on perception of facial expression, Proceedings of the 2nd International Symposium on Mobilitence in Awaji, 105-108, 2007
551. Matsumiya, K., Sugiyama, H., Shioiri, S., Kuriki, I. Effects of auditory information reading, Proceedings of the 2nd International Symposium on Mobilitence in Awaji, 97-100, 2007
552. Lee, S., \*Shioiri, S. & Yaguchi H., Stereo channels with different temporal frequency tunings, Vision Research, 47, 3258-327, 2007
553. Kuriki, I. Aftereffect of adaptation to chromatic notched-noise stimulus, Journal of the Optical Society of America A, 24, 7, 1858-1872, 2007
554. Tetsunari Inamura, Tomohiro Shibata, Interpolation and Extrapolation of Motion Patterns in the Proto-symbol Space, International Conference on Neural Information Processing, 2007
555. Jean C. Quinton, Tetsunari Inamura, Human-Robot Interaction Based Learning for Task-Independent Dynamics Prediction, Proc. of the Seventh International Conference on Epigenetic Robotics, 133-140, 2007
556. Tetsunari Inamura, Behavior Adaptation and Induction in Unknown Situation based on Multimodal Mimesis Model, 2nd International Symposium on Mobilitence, 85-88, 2007
557. Tetsunari Inamura, Behavior Imitation and Induction for Humanoid robots based on mimesis model, IJMEKO/SICE/IEEE International Symposium on Measurement, Analysis and Modeling of Human Functions (ISHF2007), 211-218, 2007
558. T. Inamura, T. Kawaji, T. Sonoda, K. Okada and M. Inaba, Cooperative Task Achievement System between Humans and Robots based on Stochastic Memory Model of Spatial Environment, Lecture Notes in Artificial Intelligence, 4384, 77-87
559. Kawase, T., Shin, D., Koike, Y. Visuomotor coordination in ball catching task, The 3rd International Symposium on Modeling of Human Functions, 129-134, 2007
560. Kambara Hiroyuki, Kim Kyoungsik, Shin Duk, Sato Makoto, & Koike Yuharu, Motor control-learning model for arm's reaching movement without desired trajectory, The 3rd International Symposium on Modeling of Human Functions, 181-187, 2007
561. DeSalle, Charles S., Sato, Mikoto, and Koike Yasuharu, EMG Vowel Recognition using a Support Vector Machine, The 3rd International Symposium on Modeling of Human Functions, 227-232, 2007
562. NPUTAMA, A. TAKEMOTO, YKOIKE, K. NAKAMURA, Serial Processing of information from facial emotion evidence from an ERP study, Neuroscience 2007, 2007
563. Toshihiro Kawase, Duk Shin, Yasuharu Koike, Unrealistic condition between visual and haptic stimuli in ball catching task, The 2nd International Symposium on Mobilitence, 89-92, 2007
564. Nogahta P. Utama, Atsushi Takemoto, Yasuharu Koike, Katsuki Nakamura, Serial Processing of Emotional Type and Intensity evidence from an ERP study, 14th International Conference on Neural Information Processing, 119, 2007
565. Kyurwan Chai, Hideaki Hirose, Yoshio Sakurai, Toshio Iijima, Yasuharu Koike, Prediction of arm trajectory from the neural activities of the primary motor cortex using a modular artificial neural network model, 14th International Conference on Neural Information Processing, 122, 2007
566. Yusuke Maeda, Tatsuya Ushioda, Analysis of Human Pivoting Operations Using Hidden Markov Models, Proc. of 2nd Int. Symp. on Mobilitence, 93-96, 2007
567. Yusuke Maeda, Tatsuya Ushioda, Hidden Markov Modeling of Human Pivoting, J. of Robotics and Mechatronics, 19, 4, 444-447, 2007
568. Toshiya Matsumura, Neuro-economics in chicks, LBRO (International Brain Research Organization) satellite meeting on "Brain mechanisms, cognition and behaviour in birds" July 19-23, Heron Island, Queensland, Australia, 2007
569. Ai Kawamori, Toshiya Matsumura, Are chicks optimal foragers? Discounting food value by distance and risk, The 30th International Ethological Conference (IEC2007), August 15-23, Halifax, Nova Scotia, Canada, 2007
570. Matsumura, T., Economical decision making in chicks: brain mechanisms meet foraging ecology, The 39th Annual General Meeting of European Brain and Behaviour Society, September 15-19, Trieste, Italy, 2007
571. Yamaguchi, S., Katagiri, S., Hirose, N., Fujimoto, Y., Mori, M., Fujii-Taira, I., Takano, T., Matsumura, T., and Homma, K. In-vivo gene transfer into newly hatched chick brain by electroporation, NeuroReport, 18, 735-739, 2007
572. Matsumura, T., Kawamori, A., and Bem-Sojka, T. Neuro-economics in chicks: foraging choices based on delay, cost and risk, Brain Research Bulletin, in press
573. Yamaguchi, S., Fujii-Taira, I., Katagiri, S., Izawa, E.-I., Fujimoto, Y., Takeuchi, H., Takano, T., Matsumura, T., and Homma, K. J. Gene expression profile in cerebrum in the filial imprinting of domestic chicks (*Gallus gallus domesticus*), Brain Research Bulletin, in press
574. Yamaguchi, S., Fujii-Taira, I., Marukami, A., Hirose, N., Aoki, N., Izawa, E.-I., Fujimoto, Y., Takano, T., Matsumura, T., and Homma, K. J. Upregulation of microtubule-associated protein 2 accompanied by the filial imprinting of domestic chicks (*Gallus gallus domesticus*), Brain Research Bulletin, in press
575. Takachi, Y., \*Ishida, F. and Sawada, Y., Enhancement of proactivity in hand tracking by the discretization of visual information, Proc of 3rd International Symposium on Measurement, Analysis and Modeling of Human Functions, 219-225, 2007, 219-225, 2007
576. F. Ishida and Y. Sawada, Semi-analytical transient solution of a delayed differential equation and its application to the tracking motion in the sensory-motor system, Physical Review E, 75, 9, 12901, 2007
577. \*Akira Murata, Hiroaki Ishida, Representation of bodily self in the multimodal parieto-premotor network, In: Representation and Brain, edited by Shintaro Funahashi, Springer Verlag, 151-176, 2007
578. Akira Murata, Self-based on the body, 2nd annual symposium on Japanese-French frontier of Science, 2007
579. \*Akira Murata and Hiroaki Ishida, Bodily self and others representation in the brain, 2nd International symposium on the Mobilitence in Awaji 2007, June Awaji, 30-33, 2007
580. Hiroaki Ishida and Akira Murata, Representation of others' body parts by visuo-tactile bimodal neuron in area VII, 2nd International symposium on the Mobilitence in Awaji 2007, June Awaji, 109-112, 2007
581. Elena Bona, Abdebaouh Belmalh, Roberta Calzavara, Marzio Gerbella, Akira Murata, Stefano Rozzi and \*Giuseppe Luppino, Cortical connections of the macaque anterior intraparietal (AIP) area, Cerebral cortex [Epub ahead of print], 2007
582. R. Yokoya, T. Ogata, J. Tani, K. Komatani, and H. G. Okuno, Discovery of other individuals by projecting a self-model through imitation, Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS2007), 1009-1014, 2007
583. T. Ogata, M. Murase, J. Tani, K. Komatani, and H. G. Okuno, Two-way translation of compound sentences and arm motions by recurrent neural networks, Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS2007), 1858-1863, 2007
584. H. Arie, S. Sugano, and J. Tani, Constructive Approach to Understanding the Active Learning Process of Adaptation within a Given Task Environment, Proc. of 2nd Int. Symp. on Mobilitence, 77-80, 2007
585. Y. Yamashita, T. Okamura, K. Okano, and J. Tani, Function of the sensor-motor nucleus Nif in generation of complex syntactical song in the Bengalese Finch, Proc. of 2nd Int. Symp. on Mobilitence, 101-104, 2007
586. S. Nishide, T. Ogata, J. Tani, K. Komatani, and H. G. Okuno, Predicting Object Dynamics from Visual Images through Active Sensing Experiences, Proc. of IEEE Int. Conf. on Robots and Automation (ICRA2007), 2501-2506, 2007
587. T. Ogata, S. Matsumoto, J. Tani, K. Komatani, and H. G. Okuno, Human-Robot Cooperation using Quasi-symbols
- Generated by RNNPB Model, Proc. of IEEE Int. Conf. on Robots and Automation (ICRA2007), 2156-2161, 2007
588. R. Yokoya, T. Ogata, J. Tani, K. Komatani, and H. G. Okuno, Experience Based Imitation Using RNNPB, Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS2006), 3669-3674, 2006
589. I. Igar, C. Hirata, and J. Tani, Computational Model for Sequence Learning: Generalization and Differentiation Dynamics of Learning Modules, Proc. of 5th Int. Conf. on Development and Learning (ICDL2006), 45-1-45-6, 2006
590. R. Yokoya, T. Ogata, J. Tani, K. Komatani, and H. G. Okuno, Robot Imitation from Active-Sensing Experiences, Proc. of 5th Int. Conf. on Development and Learning (ICDL2007), 27-1-27-6, 2006
591. J. Tani, On the interactions between top-down anticipation and bottom-up regression, Frontiers in Neurobotics, 1, 2007
592. R. Yokoya, T. Ogata, J. Tani, K. Komatani, and H. G. Okuno, Experience-based imitation using RNNPB, Advanced Robotics, 21, 12, 1351-1367, 2007
593. H. Arie, T. Ogata, J. Tani, and S. Sugano, Reinforcement learning of a continuous motor sequence with hidden states, Advanced Robotics, Special Issue on Robotic Platforms for Research in Neuroscience, 21, 10, 1215-1229, 2007
594. Yoshimasa Koyama, Regulation of muscular tonus through hypocretinergic and GABAergic systems, 5th Congress of the World Federation of Sleep Research and Sleep Medicine Societies, Cairns, 2007
595. Kodama, T., Honda, Y., Hsieh, K.C., Siegel, J.M., Lai, Y.Y., GABA Related To The Differential Effect Of Nuclei Gigantocellularis And Magnocellularis Stimulation On Muscular Activity Under The Absence Of Pontine Regulation, 5th congress of the World Federation of Sleep Research and Sleep Medicine Societies, Cairns, 2007
596. Y. Koyama, K. Takahashi, T. Kodama and K. Takakusaki, Hypothalamic regulation of muscular tonus: involvement of orexinergic and GABAergic neurons, 2nd Mobilitence International Symposium in Awaji, 2007, 166-169, 2007
597. Soya, A., Song, Y., Kodama, T., Honda, Y., Fujiki, N., Nishino, S., Cerebrospinal fluid histamine levels in rats across 24 hours and after various behavioral and pharmacological manipulations, Sleep 2007 APSS meeting, Minneapolis, 2007
598. Kodama, T., Honda, Y., Siegel, J.M., Lai, Y.Y., Changes in inhibitory amino acids release onto the ventral horn during nucleus gigantocellularis stimulation - the role of medial pons, 37th Annual Meeting of Society for Neuroscience, San Diego, CA, USA, 2007, 2007
599. Hsieh, K.C., Nguyen, D., Kodama, T., Siegel, J.M., Lai, Y.Y., Histamine release in substantia nigra is correlated with wakefulness, 37th Annual Meeting of Society for Neuroscience, San Diego, CA, USA, 2007, 2007
600. Hui Wang, Yoshiyuki Tanaka, Eich Jodo, Yukihiko Kayama, Akhiro Kawauchi, Tsuneharu Miki, Manabu Otsuki, Yoshimasa Koyama, Acupuncture stimulation to the sacral segment affects the state of vigilance in rats, Neuroscience Research, 57, 531-537, 2007
601. Juan Carlos Toledo Salas, Hiroshi Iwasaki, Eiichi Jodo, Markus H. Schmidt, Akhiro Kawauchi, Tsuneharu Miki, Yukihiko Kayama, Manabu Otsuki, Yoshimasa Koyama, Penile erection and micrurion events triggered by electrical stimulation of the mesopontine tegmental area, American Journal of Physiology, 292, R102-R111, 2008
602. Lapiere, J.L., Kosenko, P.O., Lyamin, O.I., Kodama, T., Mukhametov, L.M., Siegel, J.M., Cortical Acetylcholine Release Is Lateralized during Asymmetrical Slow-Wave Sleep in Northern Fur Seals, Journal of Neurosci, 27, 44, 11999-12006, 2007
603. Imai, Y., Inoue, H., Katzoka, A., Hua Qin, W., Masuda, M., Ikeda, T., Tsukita, K., Soda, M., Kodama, T., Fuwa, T., Honda, Y., Kaneko, S., Matsumoto, S., Wakamatsu, K., Ito, S., Miura, M., Aoki, T., Itohara, S., Takahashi, R., Pael receptor is involved in dopamine metabolism in the nigrostriatal system, Neuroscience Research, 59, 413-425, 2007
604. Soya, A., Song, Y.H., Kodama, T., Honda, Y., Fujii, N., Nishino, S., CSF histamine levels in rats reflect the central histamine neurotransmission, Neuroscience Letter (in press)
605. K. Takahashi, Y. Koyama, Y. Kayama, J.-S. Lin, K. Sakai, A temporal sequence of activity changes among wake- and sleep-promoting neurons in the brainstem and posterior hypothalamus in mice, 5th congress of the World Federation of Sleep Research and Sleep Medicine Societies, Cairns, 2007
606. Noriyuki Taniguchi, Osamu Fukuyama, Tatsuo Okubo, Takafumi Suzuki, Kunihiko Mabuchi, Rat Car System: A vehicle-formed BMI system by neural signals recorded with implantable electrodes, International Symposium on Biological and Physiological Engineering, accepted, 2008
607. Takashi Sato, Takafumi Suzuki, Kunihiko Mabuchi, Independent hydraulic positioning for an implantable multi-electrode array, Proc. of the 3rd International IEEE EMBS Conference on Neural Engineering, 73-76, 2007
608. Noriyuki Taniguchi, Takafumi Suzuki, Kunihiko Mabuchi, Biocompatibility of wire electrodes improved by MPC polymer coating, Proc. of the 3rd International IEEE EMBS Conference on Neural Engineering, 122-125, 2007
609. Osamu Fukuyama, Noriyuki Taniguchi, Saeri Saito, Takafumi Suzuki, Kunihiko Mabuchi, Control of a Vehicle-formed BMI system for Rats by Neural Signals Recorded in the Motor Cortex, Proc. of the 3rd International IEEE EMBS Conference on Neural Engineering, 394-397, 2007
610. Takafumi Suzuki, Osamu Fukuyama, Noriyuki Taniguchi, Naoki Kotake, Shoji Takeuchi, Mसानar Kunimoto, Kunihiko Mabuchi, Development of neural probes and their applications to neuroprostheses, Japan-Italy International Seminar, 2007
611. Takashi Sato, Takafumi Suzuki, Kunihiko Mabuchi, Fast automatic template matching for spike sorting based on Davies-Bouldin validation indices, Proc. of 29th International Conference of the IEEE EMBS, 3200-3203, 2007
612. Tatsuo Okubo, Noriyuki Taniguchi, Osamu Fukuyama, Takafumi Suzuki, Kunihiko Mabuchi, Characterization of head pitch cells in rats, Neuroscience 2007, 2007
613. Takafumi Suzuki, Osamu Fukuyama, Noriyuki Taniguchi, Shoji Takeuchi, Kunihiko Mabuchi, BMI system Rat Car as a tool for neuroscience, Proc. of the 2nd International Symposium on Mobilitence, 45-46, 2007
614. Osamu Fukuyama, Noriyuki Taniguchi, Takafumi Suzuki, Kunihiko Mabuchi, Estimation of Locomotion Speed and Directions Changes to Control a Vehicle Using Neural Signals from the Motor Cortex of Rat, Proceedings of the 28th IEEE EMBS Annual International Conference, 1138-1141, 2006
615. Yasuhiko Kato, Isuru Saito, Takayuki Hoshino, Takafumi Suzuki, Kunihiko Mabuchi, Preliminary Study of Multichannel Flexible Neural Probes Coated with Hybrid Biodegradable Polymer, Proceedings of the 28th IEEE EMBS Annual International Conference, 660-663, 2006
616. Takashi Sato, Takafumi Suzuki, Kunihiko Mabuchi, A new multi-electrode array design for chronic neural recording, with independent and automatic hydraulic positioning, Journal of Neuroscience Methods, 160, 45-51, 2007
617. Takafumi Suzuki, Naoki Kotake, Kunihiko Mabuchi, Shoji Takeuchi, Bundled Microfluidic Channels for Nerve Regeneration Electrodes, Proc. of the 3rd International IEEE EMBS Conference on Neural Engineering, 17-18, 2007
618. Takahashi, S., Sakurai, Y., Coding of spatial information by soma and dendrite of pyramidal cells in the hippocampal CA1 of behaving rats, European Journal of Neuroscience, 26, 2033-2045, 2007
619. Nomura, M., Sakurai, Y., Aoyagi, T., Analysis of multi-neuronal activities by means of a kernel method, Journal of Robotics and Mechatronics, 19, 364-368, 2007
620. Sakurai, Y., How can we detect ensemble coding by cell assembly, Representation and Brain (Springer), 249-270, 2007
621. Sakurai, Y., Brain-machine interface to detect real dynamics of neuronal assemblies in the working brain, Complex Medical Engineering, Springer, 407-412, 2007
622. Takahashi, S., Sakurai, Y., Spatial information coded by the soma and dendrite of pyramidal cells in the hippocampus of behaving rats, 37th Society for Neuroscience Annual Meeting, 2007
623. Hara, K., Takahashi, S., Sakurai, Y., Hippocampal and prefrontal multi-neuronal activities during acquisition, reversal, and reacquisition of a conditional association task in rats, 37th Society for Neuroscience Annual Meeting, 米国 (2007年) 11月, 2007
624. Takahashi, M., Lauwereys, J., Sakurai, Y., Tsukada, M., Sequential coding of spatial response bias in rat hippocampal CA1 neurons, 37th Society for Neuroscience Annual Meeting, 2007
625. Takahashi, M., Lauwereys, J., Sakurai, Y., Tsukada, M., Hippocampal code for alternation sequence during fixation period, 7th International Neural Coding Workshop, 2007
626. Sakurai, Y., Takahashi, S., Brain-machine interface can detect dynamic neuronal activity and synchrony in the working brain, 2nd International Symposium on Mobilitence, 2007
627. Nomura, M., Sakurai, Y., Aoyagi, T., Kernel Analysis of Multi-neuronal Spike Trains, IEEE/ICME International Conference on Complex Medical Engineering, 2007
628. Hanakawa, T., The role of the basal ganglia-thalamo-cortical circuits for controlling human gait: Neuroimaging Evidence, 2nd International Symposium of Mobilitence, 39-40, 2007
629. Iseki, K., Hanakawa, T., Shinozaki, J., Nankaku, M., Fukuyama, H., Activation of bilateral premotor areas during both observation and imagery of gait movement, 2nd International Symposium of Mobilitence, 145-148, 2007
630. Mikuni, N., Okada, T., Enatsu, R., Miki, Y., Hanakawa, T., Urayama, S., Kikuta, K., Takahashi, J.A., Nozaki, K., Fukuyama, H., Hashimoto, N., Clinical impact of integrated functional neuroanavigation and subcortical electrical stimulation to preserve motor function during resection of brain tumors, Journal of Neurosurgery, 106, 4, 593-598, 2007
631. Lerner, A., Bagic, A., Boudreau, E.A., Hanakawa, T., Pagan, F., Mari, Z., Bara-Jimenez, W., Akisu, M., Gamaux, G., Simmons, J.M., Sato, S., Murphy, D.L., Hallett, M., Neuroimaging of neuronal circuits involved in tic generation in patients with Tourette syndrome, Neurology, 68, 23, 1979-1987, 2007
632. Shinozaki, J., Hanakawa, T., Fukuyama, H., Heterospecific and conspecific social cognition encoded in the anterior cingulate

- cortex, *Neuroreport*, 18, 10993-998, 2007
633. Fushimi Y, Miki Y, Urayama SI, Okada T, Mori N, Hanakawa T, Fukuyama H, Togashi K, Gray matter-white matter contrast on spin-echo T1-weighted images at 3 T and 1.5 T: a quantitative comparison study, *European Radiology*, 17, 11, 2921-2925, 2007
634. Namiki C, Hirao K, Yamada M, Hanakawa T, Fukuyama H, Hayashi T, Muraï T, Impaired facial emotion recognition and reduced amygdala volume in schizophrenia, *Psychiatry Research*, 156, 1, 23-32, 2007
635. Fushimi Y, Miki Y, Okada T, Yamamoto A, Mori N, Hanakawa T, Urayama SI, Aso T, Fukuyama H, Kikuta KI, Togashi K, Fractional anisotropy and mean diffusivity: comparison between 3.0-T and 1.5-T diffusion tensor imaging with parallel imaging using histogram and region of interest analysis, *NMR in Biomedicine*, 20, 8, 743-748, 2007
636. Hanakawa T, Dimiyama MA, Hallett M, The representation of blinking movement in cingulate motor areas: a functional magnetic resonance imaging study, *Cerebral Cortex*, in press
637. Aso T, Hanakawa T, Matsuo K, Tonna K, Shibasaki H, Fukuyama H, Nakai T, Subregions of human parietal cortex selectively encoding object orientation, *Neuroscience Letters*, 415, 3, 225-230, 2007
638. Sawamoto N, Honda M, Hanakawa T, Aso T, Inoue M, Toyoda H, Ishizu K, Fukuyama H, Shibasaki H, Role of the striatum in cognitive slowing in Parkinson's disease, *Neurology*, 68, 13, 1062-1068, 2007
639. Yamada M, Namiki C, Hirao K, Hanakawa T, Fukuyama H, Hayashi T, Muraï T, Social cognition and frontal lobe pathology in schizophrenia: A voxel-based morphometric study, *Neuroimage*, 35, 1, 292-298, 2007
640. Abe M, Hanakawa T, Takayama Y, Kuraki C, Ogawa S, Fukuyama H, Functional coupling of human prefrontal and premotor areas during cognitive manipulation, *Journal of Neuroscience*, 27, 13, 3429-3438, 2007
641. Hanakawa T, Hosoda C, Shindo S, Honda M, Mental rotation of hands and feet involves somatotopically organized brain regions, *Neuroscience Research*, 58, suppl 1, S60, 2007
642. Shirazaki J, Sawamoto N, Muraï T, Hanakawa T, Fukuyama H, Neural basis of emotional facial recognition between parents and children, *Neuroscience Research*, 58, suppl 1, S64, 2007
643. Ban H, Yamamoto H, Hanakawa T, Urayama SI, Aso T, Fukuyama H, Ejima Y, Spatial specificity of V1/V2 responses to an occluded surface, *Neuroscience Research*, 58, suppl 1, S153, 2007
644. Yamamoto T, Takahashi S, Hanakawa T, Urayama SI, Aso T, Fukuyama H, Ejima Y, Different roles of the parietal and lateral occipito-temporal cortex for 3D perception from motion, *Neuroscience Research*, 58, suppl 1, S214, 2007
645. Hanakawa T, Dimiyama MA, Hallett M, Motor planning, imagery and execution: a time-course study with functional MRI, *Cereb Cortex*, (in press)
646. Matsuyama K, Ishiguro M, Aoki M, Descending routes of locomotor driving signals involved in the generation of coordinated quadrupedal locomotion in decerebrate rabbits, Abstract for 37th Annual Meeting of Society for Neuroscience, 924.11, 2007
647. Matsuyama K, Kobayashi S, Ishiguro M, Aoki M, Brainstem-spinal cord mechanisms involved in the generation of coordinated hopping locomotion in rabbits, Proceedings of The 2nd International Symposium on Mobilignce, 157-160, 2007
648. Matsuyama K, Ishiguro M, Aoki M, Hindlimb locomotor pattern evoked by the midbrain stimulation in decerebrate, paralyzed rabbits, *Neuroscience Research*, 58, Suppl, S92, 2007
649. Matsuyama K, Ishiguro M, Aoki M, Characteristics of interlimb coordination in quadrupedal locomotion of rabbits, *Journal of Physiological Sciences*, 57, Suppl, S158, 2007
650. Ishiguro M, Maeda Y, Matsuyama K, The relationship between electrical stimulus intensity and inhibitory postsynaptic currents in CA1 pyramidal cells and dentate gyrus granule cells of rat hippocampal slices, *Journal of Physiological Sciences*, 57, Suppl, S148, 2007
651. Fujito Y, Cao Y, Matsuyama K, Aoki M, Involvement of medullary GABAergic and serotonergic raphe neurons in respiratory control in rats, *Journal of Physiological Sciences*, 57, Suppl, S238, 2007
652. H. Sakamoto, I. Nouno, K. Sakakibara, M. Ito and I. Nishikawa, Prediction of Mucin-type O-glycosylation using Structure Information by Support Vector Machines, Proceedings of the 18th International Conference on Genome Informatics, 55-56, 2007
653. Yang XM, Chen YW, Ito M, and Nishikawa I, Principal Component Analysis of O-linked Glycosylation Sites in Protein Sequence, Proceedings of the 3rd International Conference on Intelligent Information Hiding and Multimedia Signal, 2007
654. Nishikawa I, Sakamoto H, Nouno I, Sakakibara K, and Ito M, Prediction of the O-Glycosylation with Secondary Structure Information by Support Vector Machines, Lecture Notes in Artificial Intelligence 4693, 335-343, 2007
655. Chen Y W, Yang XM, Ito M, and Nishikawa I, Pattern analysis and prediction of O-linked glycosylated sites in protein by principal component subspace analysis, Lecture Notes in Artificial Intelligence 4693, 326-334, 2007
656. Nishikawa I, Hayashi K, and Sakakibara K, Complex-valued Neuron to Describe the Dynamics After Hopf Bifurcation: an Example of CPG Model for a Biped Locomotion, Proceedings of 2007 International Joint Conference on Neural Networks #1097, 2007
657. Nishikawa and K. Sakakibara, A CPG Model for Multiple Gaits based on Phase Dynamics, Proceedings of the 2nd International Symposium on Mobilignce, 137-140, 2007
658. Nishikawa I, Sakamoto H, Nouno I, Sakakibara K, and Ito M, Prediction of Mucin-type O-glycosylation by Support Vector Machines, Proc. 2007 IEEE/ICME International Conference on Complex Medical Engineering, 1901-1905, 2007
659. Khoi NLD, Noishiki M, Sakakibara K, and Nishikawa I, Stock Price Forecasting using Neural Networks with Inputs selected by Genetic Algorithm, Proceedings of the 5th International Conference on Research, Innovation and Vision for the Future, Addendum Contributions, 95-100, 2007
660. Yasuaki Kuroe and Hajimu Kawakami, Vector Field Approximation by Model Inclusive Learning of Neural Networks, Lecture Notes in Computer Science, 4668, 717-727, 2007
661. Yasuaki Kuroe and Yuriko Taniguchi, Models of Orthogonal Type Complex-Valued Dynamic Associative Memories and Their Performance Comparison, Lecture Notes in Computer Science, 4668, 838-84, 2007
662. Yoshihiro Mori, Takashi Kadawaki, Yasuaki Kuroe and Takehiro Mori, A Synthesis Method of Gene Networks Based on Gene Expression by Network Learning -Realization of Separatrix, Proc. of SICE Annual Conference 2007, 1951-1957, 2007
663. Hitoshi Iima and Yasuaki Kuroe, Swarm Reinforcement Learning Algorithms -Exchange of Information among Multiple Agents, Proc. of SICE Annual Conference 2007, 1951-1957, 2007
664. Yasuaki Kuroe and Yoshihiro Mori, Neural Network Models for Identification and Realization of a Class of Discrete Events Systems, Proc. of IEEE International Conference on Systems, Man, and Cybernetics, 1363-1369, 2007
665. T. Nomura, T. Nakamura, K. Fukada, S. Sakoda, Characterizing postural sway during quiet stance based on the intermittent control hypothesis, AIP Proceeding Series, Proceed. 19th Intl Conf on Noise and Fluctuations, Tokyo, Sept 9-14, 2007, 922, 553-556, 2007
666. A. Bottero, Y. Yasutake, T. Nomura, M. Casadio, P. Morasso, Bounded stability of the quiet standing posture: An intermittent control model, *Human Movement Science*, in press, 2008
667. K. Sakakibara, H. Tamaki and I. Nishikawa, Autonomous Distributed Approaches for Pickup and Delivery Problems with Time Windows, Proceedings of SICE Annual Conference 2007, #3B15-2, 2007
668. Takei T, Seki K, Control of primate grasping movement by spinal cord, Proceedings of 2nd International symposium on Mobilignce, , , 153-157, 2007
669. Takei T, Seki K, Spino-muscular coherence in monkeys performing a precision grip task, *Journal of Neurophysiology* (in press), 2008
670. Seki K, Kizuka T, Yamada H, Reduction in maximal firing rate of motoneurons after 1-week immobilization of finger muscle in human subjects, *Journal of Electromyography and Kinesiology*, 17, 2, 113-120, 2007
671. Seki K, Takei T, Modulation of spinal unit responses evoked from muscle afferents in a monkey performing an instructed delay task, Proceedings of the 30th annual meeting of the Japan neuroscience society, 58S1, S33, 2007
672. Takei T, Seki K, Spino-muscular coherence in monkeys performing a precision grip task, Proceedings of the 30th annual meeting of the Japan neuroscience society, 58S1, S151, 2007
673. Seki K, Takei T, Primary afferent depolarization evoked in monkey cervical spinal cord by natural tactile stimulation of cutaneous afferent, Proceedings of the 84th annual meeting of the physiological society of Japan, 57, suppl, S68, 2007
674. Miura T\*, Molecular basis underlying Daphnia polyphenism, *Daphnia Genome Consortium Meeting*, 2007
675. Suehiro Y, Imada H, Okuyama T, Kubo T, and Takeuchi H\*, Analysis of adaptive behaviors of small fishes by using combination of mathematical modeling and molecular biological approach, Proceedings of the Second International Symposium on Mobilignce, 219-222, 2007
676. M. Ozaki and T. Nakamura, Roles of NO cascade and G proteins in transduction and adaptation of the sugar receptor cell in the blowfly, *Phormia regina*, *SEB Annual General Meeting*, 2007
677. M. Ozaki, Comparative study of nestmate recognition of ant species, *International Congress of Comparative Physiology and Biochemistry*, 2007
678. Hanai and M. Ozaki, Scale free dynamics in the locomotor activity of ant, *International Congress of Comparative Physiology and Biochemistry*, 2007
679. M. Ozaki, Chemical input and neuronal system for aggressiveness in a Japanese carpenter ant, 4th Asian-Pacific Conference of Chemical Ecology, 2007
680. M. Kobayashi-Kidokoro, M. Iwakura, S. Dujwara, S. Higashi and M. Ozaki, The nestmate recognition aggressiveness in unicolonial ant *Formica yessensis*, 4th Asian-Pacific Conference of Chemical Ecology, 2007
681. K. Ishiura, Y. Satoji, H. Anonuma and M. Ozaki, Morphological investigation of aggressive center in the antennal lobe of *Camponotus japonicus*, 4th Asian-Pacific Conference of Chemical Ecology, 2007
682. K. Nishida, T. Maeda and M. Ozaki, Appetite change by odor experience in the blowfly, *Phormia regina*, 4th Asian-Pacific Conference of Chemical Ecology, 2007
683. H. Okamoto, A. Nishimura Masanobu Ito, Toshiyuki Takano and M. Ozaki, Study on appetite regulation mechanism in a novel *Drosophila melanogaster* mutant, 4th Asian-Pacific Conference of Chemical Ecology, 2007
684. M. Hojo, A. Wada-Katsumata, T. Akino, S. Yamaguchi, M. Ozaki and R. Yamazaki, Intracolonic Chemical Mimicry in ant parasitic inquiline *Niphandia fusca*, 4th Asian-Pacific Conference of Chemical Ecology, 2007
685. A. Wada-Katsumata, M. Ozaki and R. Nishida, Female's specific gustatory perception of the nuptial gift in the german cockroach, 4th Asian-Pacific Conference of Chemical Ecology, 2007
686. S. Yui, A. Wada-Katsumata, M. Ozaki, R. Kanzaki, S. Niki, N. Mori and R. Nishida, Electrophysiological analysis of oviposition stimulants on tarsal chemosensilla in a citrus swallowtail *Papilio xuthus*, 4th Asian-Pacific Conference of Chemical Ecology, 2007
687. Y. Murata, A. Wada-Katsumata, S. Matsumoto, M. Ozaki, and R. Nishida, Behavioral and electrophysiology analyses of larval feeding stimulants for a primitive swallowtail butterfly, *Sericinus monteki*, in the host plant, *Aristolochia debilis*, 4th Asian-Pacific Conference of Chemical Ecology, 2007
688. M. Ozaki, Ant nestmate and non-nestmate discrimination by a novel contact chemosensory sensillum, 5th International Symposium on Molecular and Neural Mechanism of Taste and Olfaction, 2007
689. Miura T\*, Imai M, Predator-induced polyphenism in *Daphnia pulex*, *Evolution*, 2007, 2007
690. Miura T\*, Comette R, Juvenile hormone action during soldier differentiation in the damp-wood termite, *JH*, 2007
691. Koshikawa S\*, Miura T, JHA-induced soldier differentiation and gene expression in the damp-wood termite, *Hodotermopsis sjostedii*, *JH*, 2007
692. Miura T\*, Molecular basis for social behavior and caste differentiation in termites, *Neuro*, 2007, 2007
693. Michiko Nishikawa, Hiroshi Nishino, Yoko Misaka, Maiko Kubita, Eriko Tsuji, Yui Satoji, Mamiko Ozaki and Fumio Yokohari, Sexual dimorphism in the antennal lobe structure of the ant, *Camponotus japonicus*, *Zool Sci*, in press, 2008
694. Fabien Lacaille, Makoto Hiroi, Robert Twele, Toshiyuki Inoshita, Daisuke Umemoto, Gerard Maniere, Frederic Marion-Poll, Mamiko Ozaki, Witko Franke, Matthew Cobb, Claude Zeveraets, Teichi Taninuma and Jean-Francois Ferveur, An inhibitory sex pheromone tastes bitter for *Drosophila* males, *PLoS ONE*, 2, 7, e661, 2007
695. Ishikawa Y, Koshikawa S, Miura T\*, Differences in mechanosensory hairs among castes of the damp-wood termite *Hodotermopsis sjostedii* (Isoptera: Termitidae), *Sociobiology*, 50, 3, 895-907, 2007
696. Ishikawa A, Miura T\*, Morphological differences between wing morphs of two Macrocephali aphid species, *Acyrtosiphon pisum* and *Megoura crassicauda* (Hemiptera, Aphididae), *Sociobiology*, 50, 3, 881-893, 2007
697. Lo N\*, Engel MS, Cameron S, Nalepa CA, Tokuda G, Grimaldi D, Kitade O, Krishna K, Klass K-D, Mackawa K, Miura T, Thompson GJ, Save Isoptera. A comment on Inward et al., *Biology Letters*, 3, 5, 562-563, 2007
698. Comette R, Matsumoto T, Miura T\*, Histological analysis on fat body development and molting events during soldier differentiation in the damp-wood termite *Hodotermopsis sjostedii* (Isoptera, Termitidae). *Zool Sci*, 24, 11, 1066-1074, 2007
699. Ikemoto Y\*, Kawabata K, Miura T, Asama H, Mathematical model of population ratio control and fluctuation characteristic in termite caste differentiation, *J Robotics Mechatronics*, 19, 4, 2007
700. Brandl R\*, Hyodo F, von Korf-Schmising M, Mackawa K, Miura T, Takemitsu Y, Matsumoto T, Abe T, Bagine R, Kab MD, Divergence times in the termite genus *Macrotermes* (Isoptera: Termitidae), *Mol Phylogen Evol*, 45, 239-250, 2007
701. Fujita A, Miura T\*, Matsumoto T, Differences in cellulose digestive systems among castes in two termite lineages, *Physiol Entomol*, in press, 2008
702. Ishikawa A, Hongo S, Miura T\*, Morphological and histological examination of polyphenic wing formation in the pea aphid *Acyrtosiphon pisum* (Hemiptera, Hexapoda), *Zoomorphology*, in press, 2008
703. M. Ozaki and T. Nakamura, Chemosensory regulation of feeding in the blowfly. Several studies after *The Hungry Fly*, *Zell*, 24, 11, in press, 2008
704. Hideaki Takeuchi, Establishment of behavior assays using adult Medaka fish, The 54th NIBB Conference New Frontiers for the Medaka Model Genome, Bioresources and Biologin, in press, 2007
705. Hori S, Takeuchi H\*, and Kubo T, Associative learning and discrimination of motion cues in the harnessed honeybee *Apis mellifera*, *L.J. Comp. Physiol. A*, 193, 825-833, 2007
706. Hidetoshi Ikemoto, Noriko Sasayama, Ryuichi Okada, Eisuro Ito, Behavioral analysis of honeybee waggle dance and its effect on foraging, 2nd International Symposium on Mobilignce in Awaji, 223-226, 2007
707. Hidetoshi Ikemoto, Ryohi Kanzaki, Hiroshi Anonuma, Masakazu Takahata, Makoto Mizunuma, Koji Yasuyama, Nobuyuki Matsui, Fumio Yokohari, Shiro Usui, Development of Invertebrate Brain Platform: Management of research resources for invertebrate neuroscience and neuroethology, 14th International Conference on Neural Information Processing, 2007
708. Ryuichi Okada, Hidetoshi Ikemoto, Noriko Sasayama, Hiroshi Anonuma, Daisuke Kurabayashi, Eisuro Ito, The dance of the honeybee: how do honeybees dance to transfer food information effectively?, *Acta Biologica Hungarica*, in press, 2008
709. Hidetoshi Ikemoto, Takuto Nishioka, Takuya Hachida, Ryohi Kanzaki, Youichi Seki, Izumi Ohzawa, Shiro Usui, Development and application of CMS-based database modules for neuroinformatics, *Neurocomputing*, 70, 212-2128, 2007
710. Hidetoshi Ikemoto, Ryohi Kanzaki, Youichi Seki, Tomoki Kazawa, Teijiro Isokawa, Nobuyuki Matsui, Chapter 9 - Web Based Resource Management and Its Application in the Laboratory, *Neurocomputing Research Developments* (Editors: Hugo A. Svensson), 223-239, 2008
711. Tadahiro Taniguchi, Kenji Ogawa, and Tetsuo Sawaragi, Implicit estimation of other's intention without direct observation of actions in a collaborative task: Situation-Sensitive Reinforcement Learning, *SICE Annual Conference 2007*, in CD-ROM, 2007
712. Tadahiro Taniguchi, Tetsuo Sawaragi, Dynamic Process of a User's Development of Multiple Internal Models of Automation Behavior Including Mode Transitions, 2nd International Symposium on Mobilignce in Awaji in CD-ROM, 2007
713. Tadahiro Taniguchi, Tetsuo Sawaragi, Incremental Acquisition of Behaviors and Signs based on Reinforcement Learning Schema Model and STD, *Advanced Robotics*, 21, 10, 1177-1199, 2007
714. Tadahiro Taniguchi, Tetsuo Sawaragi, Incremental acquisition of multiple nonlinear forward models based on differentiation process of schema model, *Neural Networks* (in press),
715. Yukio Horiguchi, Ryuichi Fukuiji and Tetsuo Sawaragi, Differentiation of Input-Output Relations to Facilitate User's Correct Awareness of Operating Mode of Automated Control System, Proc. of 2007 IEEE International Conference on Systems, Man and Cybernetics, 2570-2575, 2007
716. Kazuki Tsuji, Hisashi Ohtsuki, Reproductive allocation conflict causes worker policing in hymenopteran societies, *XV IUSSI Congress Proceedings*, 131, 2006
717. Sugawara, Collective Motions and Formations of Multi-robots Based on Simple Dynamics, Proc of 2007 IEEE/ICME Int. Conf. on Complex, Mechanical Engineering, 2007
718. Sugawara, Proportion Regulation in Division of Labor for Multi-agent System, Proc. of 2nd Int. Symp on Mobilignce, 199-202, 2007
719. Y. Hayashi, K. Sugawara, T. Uchikawa, Y. Hayakawa, T. Kikuchi, K. Tsuji, Analysis and Modeling of Ants' Behavior from Single to Multi-body, Proc. of 13th Int. Symp. on Artificial Life and Robotics, 2008
720. Nakamura M, Beppu Y, Tsuji K, Does disturbance favor dispersal? An analysis of ant migration using the colony-based lattice model, *Journal of Theoretical Biology*, 248, 2, 288-300, 2007
721. Le Breton J, Takaku, G. Tsuji, K. Brood parasitism in an invasive population of the pest ant *Pheidole megacephala*, *Insectes Sociaux*, 53, 2, 168-171, 2006
722. Kikuchi T, Tsuji K, Ohnishi H, Le Breton J, Caste-biased acceptance of non-nestmates in a polygynous ponerine ant, *Animal Behaviour*, 73, 4, 559-565, 2007
723. Tomonori Kikuchi, T. Mizuaki, S. Tsuji, K. Ohnishi, S. Takahashi, J. Nakajima, Y. Small queens and big headed workers in a monomorphic ponerine ant, *Naturwissenschaften*, in press, 2008
724. Hayashi R, Tsuji K, Spatial distribution of turtle barnacles on the green sea turtle, *Chelonia mydas*, *Ecological Research*, 23, 1, 123-125, 2008
725. Suwabe M, Ohnishi H, Kikuchi T, Tsuji K, Nestmate discrimination in the queenless ponerine ant *Diacamma* sp. from Japan, *Entomological Science*, 10, 1, 7-10, 2007
726. A. Fujimura, K. Hotta and K. Oka, Visualization of neuronal activity patterns in female of zebra finches for discrimination

- of song birds, *mobiligence symposium*, 2007
727. A. Fujimura, H. Ogawa, K. Hotta and K. Oka, Analysis of Arc mRNA expression in female zebra finch brain for song discrimination, *Society for Neuroscience 2007* (San Diego, USA), Poster 6465/KKK10, 2007
728. \*Hidehiko Takahashi, Motoichiro Kato, Mika Hayashi, Yoshiro Okubo, Akhiro Takano, Hiroshi Ito, Tetsuya Suhara, Memory and frontal lobe functions; possible relations with dopamine D2 receptors in the hippocampus, *NeuroImage*, 34, 1643-1649, 2007
729. \*Tatsuro Oda, Kuniaki Tsuchiya, Tetsuki Arai, Takashi Togo, Hirotake Uchikado, Rohan de Silva, Andrew Lees, Haruhiko Akiyama, Chie Haga, Kenji Ikeda, Motoichiro Kato, Yuji Kato, Tsunekatsu Hara, Mitsumoto Onaya, Koji Horii, Hiroshi Teramoto, Iaru TomiNaga, Pick's disease with Pick bodies: An unusual autopsy case showing degeneration of the pontine nucleus, dentate nucleus, Clarke's column, and lower motor neuron, *Neuropathology*, 27, 81-89, 2007
730. \*Yoshiyuki Shibukawa, Tetsuya Ishikawa, Yutaka Kato, Zhen-Kang Zhang, Ting Jiang, Masaru Shintani, Masaki Shimono, Toshifumi Kumai, Takashi Suzuki, Motoichiro Kato, Yoshio Nakamura, Cerebral Cortical Dysfunction in Patients with Temporomandibular Disorders in Association with Jaw Movement Observation, *Pain*, 128, 180-188, 2007
731. \*Toshiyuki Kunihara, Motoichiro Kato, Accessibility and utilization of mental health care in Bali, *Psychiatry and Clinical Neuroscience*, 61, 205, 2007
732. Yoko Tanaka, \*Motoichiro Kato, Taro Muramatsu, Fumie Saito, Seiji Sato, Haruo Shintaku, Yoshiyuki Okano, Hiroshi Kondo, Tatsushi Nakazawa, Early initiation of L-dopa therapy enables stable development of executive function in tetrahydropterin deficiency, *Developmental Medicine and Child Neurology*, 49, 372-376, 2007
733. \*Yutaka Kato, Taro Muramatsu, Motoichiro Kato, Masaru Shintani, Haruo Kashima, Activation of right insular cortex during imaginary speech articulation, *Neuroreport*, 18, 505-509, 2007
734. Mihoko Otake, Kohei Arai, Motoichiro Kato, Takaki Maeda, Yusuke Ikemoto, Kuniaki Kawabata, Toshinisi Takagi and Hajime Asama, Experimental analysis of the attribution of own actions to the intention of self or others by the multiple forward models, *Journal of Robotics and Mechatronics*, 19, 442-448, 2007
735. Yoshitake Akine, \*Motoichiro Kato, Taro Muramatsu, Satoshi Umeda, Masaru Minura, Yoshiyuki Asai, Shuji Tanada, Takayuki Obata, Hiroe Ikehara, Haruo Kashima, Tetsuya Suhara, Altered brain activation by a false recognition task in young abstinent alcoholic patients, *Alcoholism: Clinical and Experimental Research*, 31, 915-919, 2007
736. \*Ryoko Nakachi, Taro Muramatsu, Motoichiro Kato, Tomoko Akiyama, Fumie Saito, Fumihiko Yoshino, Masaru Minura, Haruo Kashima, Progressive prosopagnosia at a very early stage of frontotemporal lobar degeneration, *Psychogeriatrics*, 7, 155-162, 2007
737. \*Tomoko Akiyama, Motoichiro Kato, Taro Muramatsu, Satoshi Umeda, Fumie Saito, Haruo Kashima, Unilateral amygdala lesions hamper attentional orienting triggered by gaze direction, *Cerebral Cortex*, 17, 2593-2600, 2007
738. Yasushi Moriyma, Taro Muramatsu, Motoichiro Kato, Masaru Minura, Tomoko Akiyama, Haruo Kashima, Fronto-goli syndrome accompanied with prosopagnosia in a woman with a 40-year history of schizophrenia, *The Keio Journal of Medicine*, 56, 130-134, 2007
739. \*Tomoko Akiyama, Motoichiro Kato, Taro Muramatsu, Takaki Maeda, Tsunekatsu Hara, Haruo Kashima, Gaze-triggered orienting is reduced in chronic schizophrenia, *Psychiatry Research*, 17, 2593-2600, 2007
740. \*Hidehiko Takahashi, Masato Matsuura, Michihiko Koeda, Noriaki Yahata, Tetsuya Suhara, Motoichiro Kato, Yoshiro Okubo, Brain activations during judgments of positive self-conscious emotion and positive basic emotion: pride and joy, *Cerebral Cortex* (in press),
741. \*Hidehiko Takahashi, Yota Fujimura, Mika Hayashi, Harumasa Takano, Motoichiro Kato, Hiroshi Ito, Tetsuya Suhara, Enhanced dopamine release by nicotine in cigarette smokers: a double-blind randomized, placebo-controlled pilot study, *The International Journal of Neuropsychopharmacology* (in press),
742. \*Mihoko Otake, Kohei Arai, Motoichiro Kato, Takaki Maeda, Yusuke Ikemoto, Kuniaki Kawabata, Toshinisi Takagi and Hajime Asama, Experimental analysis of the attribution of own actions to the intention of self or others by the multiple forward models, *Journal of Robotics and Mechatronics*, 19, 442-448, 2007
743. \*Yasushi Moriyma, Taro Muramatsu, Motoichiro Kato, Masaru Minura, Tomoko Akiyama, Haruo Kashima, Fronto-goli syndrome accompanied with prosopagnosia in a woman with a 40-year history of schizophrenia, *The Keio Journal of Medicine* (in press), 56, 130-134, 2007
744. \*Ryosuke Arakawa, Hiroshi Ito, Akhiro Takano, Hidehiko Takahashi, Takuya Morimoto, Takeshi Sessa, Katsuya Ohta, Motoichiro Kato, Yoshiro Okubo, Tetsuya Suhara, Striatal and extrastriatal dopamine D2 receptor occupancy by paliperidone ER, *Journal of Clinical Psychopharmacology* (in press),
745. \*Hidehiko Takahashi, Tomohisa Shibuya, Motoichiro Kato, Masato Matsuura, Michihiko Koeda, Noriaki Yahata, Tetsuya Suhara, Yoshiro Okubo, Enhanced activation in the extrastriate body area by goal-directed actions, *Psychiatry and Clinical Neuroscience* (in press),
746. Hidehiko Takahashi, Motoichiro Kato, Masato Matsuura, Michihiko Koeda, Noriaki Yahata, Tetsuya Suhara, Yoshiro Okubo, Neural correlates of human virtue judgment, *Cerebral Cortex* (in press),
747. Mika Hayashi, Motoichiro Kato, Kazuo Igarashi, Haruo Kashima, Superior fluid intelligence in children with Asperger's disorder, *Brain and Cognition* (in press),
748. Susumu Higuchi, Takafumi Yuzuriba, Yoshiro Kochi, Sachio Matsushita, Tomohiro Miyakawa, Motoichiro Kato and Hiroshi Stuwaki, Clinical characteristics and treatment outcome of inpatients with alcohol dependence: results from a nationwide survey of specialized treatment hospitals, *World Psychiatry Association International Congress 2007*, 2007
749. Mika Hayashi, Teruo Hashimoto, Motoichiro Kato, Satoshi Umeda, Masaru Minura, Seiji Ogawa, Top-down Processing in Face Perception Detected by Seeing-as-face Task in fMRI Study, *International Neuropsychological Society, 2007 Joint Mid-Year Meeting*, 2007
750. Hidehiko Takahashi, Takashi Ideno, Shigetaka Okubo, Hiroshi Matsui, Kazuhisa Takemura, Eisuke Matsushima, Masato Matsuura, Motoichiro Kato, Kunihiro Asai, Yoshiro Okubo, THE IMPACT OF CHANGING THE TERM FOR SCHIZOPHRENIA ON THE IMPLICIT ATTITUDE AMONG THE GENERAL PUBLIC IN JAPAN, *World Psychiatry Association International Congress 2007*, 2007
751. Mihoko Otake, Kohei Arai, Motoichiro Kato, Takaki Maeda, Yusuke Ikemoto, Kuniaki Kawabata, Toshinisi Takagi and Hajime Asama, Experimental Analysis and Computational Simulation of the Attribution of Own Actions by the Multiple Forward Models, *ROBIO 2007, IEEE International Conference on Robotics and Biomimetics*, 2007
752. Toshiyuki Kunihara, Motoichiro Kato, Delays in seeking psychiatric care among patients with schizophrenia in Bali, *Health Knowledge, Attitudes and Practices*, eds by: Nova Biomedical Books, Nova Science Publishers, Inc., New York, 2007 (in press) , 2007
753. Yoshi Tamori, Noriyuki Tomita, Implicit activities in auditory magnetoencephalography (MEG), *Quantum Mind 2007*, 107-108, 2007
754. K. Sasaki, Reorganization of the central nervous system responding to changes in social environment in insects, *ESB Special Seminar*, 2, 2007
755. K. Sasaki and K. Harano, Potential effects of tyramine on the transition of reproductive workers in honeybees (*Apis mellifera* L.), *Physiological Entomology*, 32, 194-198, 2007
756. K. Harano, M. Sasaki and K. Sasaki, Effects of reproductive state on rhythmicity, locomotor activity and body weight in European honeybee, *Apis mellifera* (Apidae: Hymenoptera) queens, *Sociobiology*, 49, 189-200, 2007
757. K. Sasaki, K. Yamasaki and T. Nagao, Neuro-endocrine correlates of ovarian development and egg-laying behaviors in the primitively eusocial wasp (*Polistes chinensis*), *Journal of Insect Physiology*, 53, 940-949, 2007
758. K. Sasaki and T. Nagao, Reorganization of the central nervous systems in response to changes of social environment in insects, *Journal of Robotics and Mechatronics*, 19, 369-373, 2007
759. T. Miyatake, K. Tabuchi, K. Sasaki, K. Okada, Y. Nishi, K. Katayama and S. Moriya, Pleiotropic anti-predator strategies, fleeing and feigning death, correlated with dopamine levels in *Tribolium castaneum*, *Animal Behaviour*, 75, 113-121, 2007
760. Yoshi Tamori, Noriyuki Tomita, Effect of implicit response in Auditory MEG measurement, *Neuro 2007*, 151, 2007
761. Nagasaka Y., Hihara S., Iraki A. and Fujii N., Social context modulates motion-related neurons in primate parietal cortex, *Society for Neuroscience*, 748, 6, 2007
762. Fujii N., Hihara S. and Iraki A., Actor and action recognition in premotor and parietal cortex, *Society for Neuroscience*, 558, 12, 2007
763. Fujii N., Revealing adaptive social brain functions in primates, *2nd International Symposium on Mobiligence in Awaji*, 2007
764. Fujii N., Hihara S., Iraki A., Dynamic Social Adaptation of Motion Related Neurons in Primate Parietal Cortex, *PLoS ONE*, 25, e397, 2007
765. Fujii N., Hihara S., Iraki A., Social cognition in premotor and parietal cortex, *Social Neuroscience*, in press, 2007
766. Fujii N., Abba D., Kudo N., Hihara S., Okanoya K. and Iraki A., Prefrontal activity during invertebrate discrimination, *Neuroscience Research*, 59, 3257-264, 2007
767. Takenaka K., Nagasaka Y., Hihara S., Nakahara H., Iraki A., Kuniyoshi Y., Fujii N., Linear discrimination analysis of monkey's behavior in alternative free choice task, *Journal of Robotics and Mechatronics*, 19, 414-422, 2007
768. Fujii N., Social Context Dependent Modulation in Primate Parietal Cortex, *Vision*, 19, 3, 143-146, 2007
769. D. Ito, H. Adaniya, M. Nagayama, T. Uchida, and K. Gohara, Long-term measurement for spatiotemporal dynamics of cultured neural networks, *37th Annual Meeting of the society for Neuroscience Afs*, (Neuroscience 2007), San Diego, USA, 36, 22, 2007
770. M. Uchida, Y. Maehara and H. Shioya, Design of an Unsupervised Weight Parameter Estimation Method in Ensemble Learning, *14th International Conference on Neural Information Processing (ICONIP 2007)*, 253, 2007
771. M. Nagayama, T. Uchida, and K. Gohara, Temporal and Spatial Variations of Lipid Droplets during Adipocyte Division and Differentiation, *J. Lipid Res.*, 48, 19-18, 2007
772. J. Motomura, T. Uchida, M. Nagayama, K. Gohara, T. Taira, K. Shimizu and M. Sakai, Effects of additives and cooling rates on cryo-preservation process of rat cortical cells, *Physics and Chemistry of Ice* (ed. by WF. Kuhs), Royal Soc. Chemistry, 409-416, 2007
773. \*Kazuhiro Matsumoto, Ichiro Tsuda and Yuki Hosoi, Controlling Engine System a Low-Dimensional Dynamics in a Spark Ignition Engine of Motorcycle, *Z. Naturforsch. A*, 62a, 587-595, 2007
774. \*T. Tsuda and H. Fujii, Chaos Reality in the Brain, *J. of Integrative Neuroscience*, 6(2007), 6, 309-326, 2007
775. \*Y. Fukushima, M. Tsukada, I. Tsuda, Y. Yamaguchi and S. Kuroda, Spatial clustering property and its self-similarity in membrane potentials of hippocampal CA1 pyramidal neurons for a spatio-temporal input sequence, *Cogn. Neurodyn.*, 1, 305-316, 2007
776. Takaaki Aoki, Kaichiro Ota, Koji Kurata, Toshio Aoyagi, Ordering Process of Self-Organizing Maps Improved by Asymmetric Neighborhood Function, *Proceedings of ICONIP 2007*, in press
777. Takaaki Aoki, Toshio Aoyagi, Synchrony-Induced switching behavior of attractors in neural network organized by spike-timing dependent plasticity, *Proceedings of 2nd International Symposium on Mobiligence in Awaji*, 283-286, 2007
778. \*Takaaki Aoki, Toshio Aoyagi, A cooperative dynamics of network of neural oscillators between the neuronal activity and the synaptic weight, *Neuroscience Research*, 58, S112, 2007
779. \*Takaaki Aoki, Toshio Aoyagi, Synchrony-induced switching behavior of spike-pattern attractors created by spike-timing dependent plasticity, *Neural Computation*, 19, 10, 2720-2738, 2007
780. \*Takaaki Aoki, Toshio Aoyagi, Self-Organizing maps with Asymmetric Neighborhood function, *Neural Computation*, 19, 8, 2525-2535, 2007
781. \*Takaaki Takakawa, Toshio Aoyagi, Tomoki Fukui, Synchronous and asynchronous bursting states: role of intrinsic neural dynamics, *Journal of Computational Neuroscience*, 23, 2, 189-200, 2007
782. \*Takuma Tanaka, Toshio Aoyagi, Weighted scale-free networks with variable power-law exponents, *Physica D*, in press
783. \*Takuma Tanaka, Fumino Fujiyama, Masaki Nomura, Toshio Aoyagi, Takeshi Kaneko, Presynaptic AMPA receptors on the corticostriatal terminals enhance the release probability of the synaptic vesicles, *Neuroscience Research*, 58, S211, 2007
784. \*Yoshiyuki Kubota, Fuyuki Karube, Masaki Nomura, Toshio Aoyagi, Atsushi Mochizuki, Yasuo Kawaguchi, Dendritic dimensions of cortical nonpyramidal cells, *Neuroscience Research*, 58, S73, 2007
785. \*Masaki Nomura, Yoshio Sakurai, Toshio Aoyagi, Behavioral inference based on hippocampal multi-neuronal activities of rats, *Neuroscience Research*, 58, S160, 2007
786. \*Toshio Aoyagi, Yoshihiro Yoshii, Yukito Iba, Tsuyoshi Chawanya, Optimal weighted networks of phase oscillators maximizing frequency and phase orders, *STAPPYS 23, the 23rd International Conference on Statistical Physics of the International Union for Pure and Applied Physics (IUPAP)*, 225, 2007
787. \*Masaki Nomura, Yoshio Sakurai, Toshio Aoyagi, Analysis of multi-neuronal activities by means of a kernel method, *Journal of Robotics and Mechatronics*, 19, 4, 364-368, 2007
788. \*Takaaki Aoki, Toshio Aoyagi, Synchrony-induced attractor transition in cortical neural networks organized by spike-timing dependent plasticity, *Journal of Robotics and Mechatronics*, 19, 4, 409-415, 2007
789. Y. Taniiri, J. Nishii, Optimality of reaching movements based on energetic cost under the influence of signal-dependent noise, *Lecture notes in computer science, Springer-Verlag*, in press
790. Y. Taniiri, J. Nishii, Optimality of reaching movements based on energetic cost under the influence of signal-dependent noise, *Abstract of the 14th International Conference on Neural Information Processing*, 226, 2007
791. J. Nishii, Basic strategy for the selection of locomotor patterns and movement trajectories in living bodies, *Proceeding of the 2nd International Symposium on Mobiligence*, 56-59, 2007
792. Y. Hashizume, J. Nishii, Emergence of altruistic behavior with common words through natural selection, *Proceeding of the 2nd International Symposium on Mobiligence*, 287-290, 2007
793. A. Fujii, H. Suenaga, Y. Taniiri, J. Nishii, Optimality of leg swing trajectories during walking based on metabolic cost, *Proceeding of the 2nd International Symposium on Mobiligence*, 291-294, 2007
794. Y. Miyazaki, H. Maeda, T. Hioki, J. Nishii, A hierarchical learning control model of locomotor patterns of legged animals, *Proceeding of the 2nd International Symposium on Mobiligence*, 295-298, 2007
795. J. Nishii, T. Hioki, Basic concepts of the control and learning mechanism of locomotion by the central pattern generator, *Bioinspiration and Robotics: Walking and Climbing Robots*, 247-260, 2007
796. Takamatsu, A. and Gomi, T., 2/3-allometric scaling law in a two-dimensional organism, *European Conference on Complex Systems*, 07, Dresden, 2007
797. Yuki Kagawa, Masateru Ito and Atsuko Takamatsu, Synchronization in two-dimensional organism modeled with coupled maps on weighted trees, *European Conference on Complex Systems*, 07, Dresden, 2007
798. Takamatsu, A., Mobiligence in an amoeboid cell, plasmodium of *Physarum polycephalum*, *Proceedings in 2nd International Symposium on Mobiligence in Awaji*, 48-51, 2007
799. Takamatsu, A., Ito, M. and Kagawa, Y., Network geometry analysis in plasmodial slime mold, *Proceedings in 2nd International Symposium on Mobiligence in Awaji*, 275-278, 2007

## 2008

800. Plesky, C., Fagiolini, M., Wagensarma, A., Harasawa, N., Kuji, T., Asaka-Ohara, A., Kanzaki, Y., Fujishima, S., Waki, K., Nakahara, H., Hensch, T. K., & Camici, P., A Resource for Transcriptomic Analysis in the Mouse Brain, *PLoS ONE*, 3, 8, 2008
801. Nakahara, H., Shimono, M., Uchida, G. & Tanifuji, M., Stimulus-induced pairwise interaction can be revealed by information geometric approach, *Springer Lecture Notes*, in press, 2008
802. Bismark, F., Nakahara, H., Doya, K., & Hikosaka, O., Combining modalities with different latencies for optimal motor control, *Journal of Cognitive Neuroscience*, 20, 11, 1966-1979, 2008
803. Santos, G. S., Nagasaka, Y., Takenaka, K., Iraki, A., Fujii, N., & Nakahara, H., Social modulation of the prefrontal cortex, parietal cortex, and caudate activity for reward-oriented behavior, *Neuroscience Meeting Planner, Society for Neuroscience*, Online, Program No. 93.11.TT40, 2008
804. Takashi Sakurada, Hiroaki Gomi, Koji Ito, Extrinsic reference frame during bilateral finger coordination, *Neuroscience* 2008, 2008
805. Manabu Gouko, Koji Ito, Action generation model for multiple tasks based on the ecological approach, *Proceedings of the 2nd IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO2008)*, 457-458, 2008
806. Naoki Tomi, Manabu Gouko, Koji Ito, Inaccuracy of internal models in force fields and complementary use of impedance control, *Proceedings of the 2008 IEEE International Conference on Intelligent Robots and Systems (IROS 2008)*, 393-398, 2008
807. Naoki Tomi, Manabu Gouko, Koji Ito, Impedance control complements incomplete internal models under complex external dynamics, *Proceedings of The 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC2008)*, 5354-5357, 2008
808. Mitsuru Takahashi, Manabu Gouko, Koji Ito, Electroencephalogram (EEG) and Functional Electrical Stimulation (FES) System for Rehabilitation of Stroke Patients, *Proceedings of The 21th IEEE International Symposium on Computer-Based Medical Systems (CBMS 2008)*, 53-58, 2008
809. Kaveri, S. R., Nakahara, H., Uncertainty and discounting of rewards for dopamine activity by dissociating internal and physical limits, *Neuroscience Meeting Planner, Society for Neuroscience*, Online, Program No. 98.2.UU32, 2008
810. Santos, G. S., Nagasaka, Y., Takenaka, K., Iraki, A., Fujii, N., & Nakahara, H., Social Reward-Oriented Behavior in the PFC, CN, and Parietal Cortex, *The 31st Annual Meeting of the Japan Neuroscience Society (Neuroscience 2008)*, P2-07, 2008
811. Kaveri, S. R., Nakahara, H., Timing in Temporal Difference Models of Dopamine, *The 31st Annual Meeting of the Japan Neuroscience Society (Neuroscience 2008)*, P3-12, 2008
812. Nakahara, H., Analyzing neural dynamics by considering higher-order interaction and, also, the effect of time on reward prediction, *EPSC Workshop on Computational Neuroscience*, 2008
813. Nakahara, H., Effects of internal time and context representation on dopamine activity and value-based decision making, *Open Problems in Neuroscience of Decision Making*, 2008
814. Nakahara, H., Computational modeling of Basal Ganglia, *The 3rd APCTP-KAIST Summer School for Brain Dynamics*, 2008

815. Toshiyuki Kondo, Daisuke Hirakawa, Takayuki Nozawa, Sustainability and Predictability in a Lasting Human-Agent Interaction, Proc. of the Eight International Conference on Intelligent Virtual Agents (IVA08), 505-506, 2008
816. Takayuki Nozawa, Toshiyuki Kondo, Information-theoretic characterization of relative and fluctuating system-environment distinction, Proc. of Artificial Life XI, 791, 2008
817. Toshiyuki Kondo, Yuya Kobayashi, Takayuki Nozawa, Effect of Successive Experiences on Simultaneous Learning of Conflicting Visuomotor Rotations, IROS2008 Full Day Workshop, 2008
818. Toshiyuki Kondo, Osamu Arami, Takayuki Nozawa, Proposal of Anticipatory Pattern Recognition for EMG Prosthetic Hand Control, Proc. of the 2008 IEEE International Conference on Systems, Man, and Cybernetics (SMC 2008), 897-902, 2008
819. Yuki Orii, Takayuki Nozawa, Toshiyuki Kondo, Web-based Intelligent Photo Browser for Flood of Personal Digital Photographs, Proc. of International Workshop on Web Intelligence (WI08), 127-130, 2008
820. Matsushima, T., Kawamori, A., and Bern-Sojka T., Neuro-economics in chicks: foraging choices based on delay, cost and risk, Brain Research Bulletin, 76, 245-252, 2008
821. Yamaguchi, S., Fujii-Taira, I., Katagiri, S., Izawa, E.-I., Fujimoto, Y., Takeuchi, H., Takano, T., Matsushima, T., and Homma, K.J., Gene expression profile in cerebrum in the filial imprinting of domestic chicks (*Gallus gallus domesticus*), Brain Research Bulletin, 76, 275-281, 2008
822. Yamaguchi, S., Fujii-Taira, I., Murakami, A., Hirose, N., Aoki, N., Izawa, E.-I., Fujimoto, Y., Takano, T., Matsushima, T., and Homma, K.J., Upregulation of microtubule-associated protein 2 accompanied by the filial imprinting of domestic chicks (*Gallus gallus domesticus*), Brain Research Bulletin, 76, 282-288, 2008
823. Kawamori A., Matsushima T., Distinct patterns of risk sensitivity for amount and delay in foraging choices of week-old domestic chicks, Animal Cognition (in revision), 2009
824. Matsushima T., Ecology meets neuroscience: neural mechanisms of profitability-based choices in the domestic chicks, International symposium on Evolutionary studies in behavioral neuroscience, June 26, 2008, Hayama, Japan, 2008
825. Matsushima T., Ecology meets neuroscience: rationality of profitability-based choices in the domestic chicks, (invited seminar at the Department of Psychology), September 19, 2008, University of Otago, Dunedin, New Zealand, 2008
826. Amita H., Matsuura S., Matsushima T. Impulsive choice in chicks: effects of competitive foraging and SSRI (fluvoxamine), The 31th Japan Neuroscience Meeting (Neuro2008), July 9-11, Tokyo, Japan, 2008
827. Matsuura S., Amita H., Matsushima T., SSRI (fluvoxamine) elongates food-patch residence time in chicks, The 31th Japan Neuroscience Meeting (Neuro2008), July 9-11, Tokyo, Japan, 2008
828. Kawamori A., Matsushima T., Risk-sensitive choice in chick, The 31th Japan Neuroscience Meeting (Neuro2008), July 9-11, Tokyo, Japan, 2008
829. Toshihiro KAWASE, Kazuo KURASHIGE, Masato WATANABE, Hiroyuki KAMBARA, Yasuharu KOIKE, Controller of Ultrasonic Motor for Rehabilitation Robot, ISEK2008, CD-ROM, 2008
830. T. Ogawa, H. Komatsu, Condition-dependent and condition-independent target selection in macaque posterior parietal cortex, Journal of Neurophysiology, 2, in press, 2009
831. Murata A., Ishida H., Consciousness of body and mirror neuron system, Acta Medica Kinki University, 33, 1, 2, 9-21, 2009
832. Hiroaki Ishida, Kastumi Nakajima, Masahiko Inase, Akira Murata, Shared mapping of own and others' bodies in visuo-tactile bimodal area of the monkey parietal cortex, Journal of Cognitive Neuroscience (in press), 2009
833. Sakata H., Murata A., Tsutsui K., Visual space representation for action, In: Encyclopedia of Neuroscience (C. Binder MD, Hirokawa N., Windhorst U., Hirsch MC, eds) (Springer-Verlag Berlin and Heidelberg), 2008
834. Akira Murata, Hiroaki Ishida, Other's body representation referred to self body in the brain, The tenth international conference on the simulation of adaptive behavior, SAB2008 Osaka, Japan, 2008
835. Ishida H., Inase M., Murata A., Shared representation of self and other's body parts in visuo-tactile bimodal area of the monkey parietal cortex, The 6th Forum of European Neuroscience, 2008 Geneva Switzerland, 4, 0208, 2008
836. Tetsunari Inamura and Keisuke Okuno, Adaptive acquisition of mimesis model based on communication between humanoid robots, International workshop on Imitation and Coaching in Humanoid Robots, 2008
837. Tetsunari Inamura, Multimodal Sensorimotor Integration and Behavior Induction Between Other and Self Based on Mirror Neuron Model, First France-Japan Research Workshop on Human-Robot Interaction, 2008
838. J. Tani, R. Nishimoto, J. Namikawa, M. Ito, Codevelopmental learning between human and humanoid robot using a dynamic neural-network model, IEEE Trans. on Syst. Man and Cybern. Part B-Cybernetics, 38, 1, 43-59, 2008
839. R. Nishimoto, J. Namikawa, J. Tani, Learning Multiple Goal-Directed Actions Through Self-Organization of a Dynamic Neural Network Model: A Humanoid Robot Experiment, Adaptive Behavior, 16, 2/3, 166-181, 2008
840. J. Tani, R. Nishimoto, R.W. Paine, Achieving 'organic' compositionality through self-organization: Reviews on brain-inspired robotics experiments, Neural Networks, 21, 584-603, 2008
841. Y. Yamashita, J. Tani, Emergence of functional hierarchy in a multiple timescale neural network model: a humanoid robot experiment, PLoS Computational Biology, 4, 11, e1000220, 2008
842. M. Maniadiakis, J. Tani, Acquiring rules for rules: neuro-dynamical systems account for meta-cognition, Adaptive Behavior, accepted
843. H. Arie, T. Endo, T. Arakaki, S. Sugano, J. Tani, Creating novel goal-directed actions at criticality: a neuro-robotic experiment, New Mathematics and Natural Computation, in press
844. R. Nishimoto, J. Tani, Development process of functional hierarchy for actions and motor imagery: a constructivist view from synthetic neuro-robotics study, Psychological Research, accepted
845. Bando Y., Takakusaki K., Ito S., Terayama R., Kashiwayanagi M., Yoshida S., Differential changes in axonal conduction following CNS demyelination in two mouse models, European Journal of Neuroscience, 28, 1731-1742, 2008
846. Kumei S., Motomura W., Yoshizaki T., Takakusaki K., Okumura T., Troglitazone increases expression of E-cadherin and claudin 4 in human pancreatic cancer cells, Biochemical and Biophysical Research Communications (in press)
847. Takakusaki K., Tomita N., Yano M., Substrates for normal gait and pathophysiology of gait disturbances with respect to the basal ganglia dysfunction, Journal of Neurology, 255, suppl 4, 19-29, 2008
848. Takakusaki K., Forebrain control of locomotor behaviors, Brain Research Review, 57, 192-198, 2008
849. Okumura T., Takakusaki K., Role of orexin in central regulation of gastrointestinal functions, Journal of Gastroenterology, 43, 652-660, 2008
850. Takakusaki K., Okumura T., Neurobiological Basis of Controlling Posture and Locomotion, Advanced Robotics, 22, 1629-1663, 2008
851. Adachi M., Nonaka S., Katada A., Arakawa T., Ota R., Harada H., Takakusaki K., Harabuchi Y., Carbachol injection into the pontine reticular formation depresses laryngeal muscle activities and airway reflexes in decerebrate cats, Neuroscience Research (in press)
852. Takakusaki K., Substrates for execution for gait performance with respect to the basal ganglia function, IROS2008 Full day Workshop, September 26th 2008, Nice, France
853. Takakusaki K., Basal ganglia efferents to the brainstem control postural muscle tone by modulating the activity of cholinergic PPN neurons via GABA<sub>A</sub>-receptors in cats, S.F.N. 2008
854. An Qi, Ikemoto Y., Asama H., Matsuoka H., Chugo D., Takakusaki K., Extraction of Behavior Primitives in Human Standing-up Motion for Development of Power Assisting Machine, ROBIO 2008
855. Takakusaki K., Background excitability of spinal reflex arcs are modulated by muscle tone inhibitory system, Neuroscience 2008
856. Atsushi Chiba, Ken-ichi Oshio and Masahiko Inase, Striatal Neurons Encoded Temporal Information in Duration Discrimination Task, Experimental Brain Research, 186, 671-676, 2008
857. Ken-ichi Oshio, Atsushi Chiba and Masahiko Inase, Temporal Filtering by Prefrontal Neurons in Duration Discrimination, European Journal of Neuroscience, 28, 11, 2333-2343, 2008
858. Atsushi Chiba, Ken-ichi Oshio and Masahiko Inase, Effects of Isotonic Contraction Exercised with Deferens of Guinea-Pigs under Pain-Related Drugs, 16th International Conference on Biomechanics, 275-277, 2008
859. N. Wada, F. Mori, et al, Investigation and characterization of rat bipedal walking models established by a training program, Brain Research, 1243, 70-77, 2008
860. T. Hosokido, F. Mori, et al, Characteristics of H- and M-waves recorded from rat forelimbs, Neuroscience Letters, 450, 239-241, 2009
861. F. Mori, K. Nakajima and S. Aoi, Cortical motor areas in the postural and locomotor control, XXV Barany Society Meeting, 2008
862. Shogo Endo, Fumihiko Shutoh, Tung Le Dinh, Takehito Okamoto, Toshio Ikeda, Michiyuki Suzuki, Shigenori Kawahara, Dai Yanagihara, Yamato Sato, Kazuyuki Yamada, Yutaka Karino, Nicholas A. Hartzell, Kazuhiko Yamaguchi, Shigeyoshi Itohara, Angus Naim, Paul Greengard, Soichi Nagao, and Masao Ito, Dual involvement of G-substrate in motor learning revealed by gene deletion, Proceedings of the National Academy of Sciences of the United States of America, in press, 2009
863. Kiyoi Matsuyama, Kaoru Takakusaki, Organizing Principles of Axonal Projections of the Long Descending Reticulospinal Pathways and Their Targets' Spinal Commissural Neurons: With Special Reference to the Locomotor Function, Handbook on White Matter: Structure, Function and Changes (Editors: Westland TB., Calton R.N.), in press, 2009
864. Onuma Boonyarom, Naoki Kozuka, Kiyoi Matsuyama, Shinji Murakami, Effect of Electrical Stimulation to Prevent Muscle Atrophy on Morphological and Histological Properties of Hindlimb Suspended Rat Hindlimb Muscles, American Journal of Physical Medicine & Rehabilitation, 88, in press, 2009
865. Kiyoi Matsuyama, Masanori Ishiguro, Mamoru Aoki, Roles of supraspinal signals and sensory feedbacks in generation of coordinated quadrupedal locomotion in rabbits, Journal of Physiological Sciences, 58, Suppl. S195, 2008
866. Natori, S., Yoshimi, K., Takahashi, T., Kagohashi, M., Oyama, G., Shimo, Y., Hattori, N., Kitazawa, S., Subsecond reward-related dopamine release in the mouse dorsal striatum, Neuroscience Research (in press), 2008
867. Ono, F., & Kitazawa, S., The effect of marker size on the perception of an empty interval, Psychonomic Bulletin & Review, 16, 1, 182-189, 2009
868. G. Oyama, K. Yoshimi, S. Natori, Y. Chikaoka, Y. Shimo, S. Kitazawa, R. Takahashi, N. Hattori, Reduced dopamine release in the striatum of Parkin knockout mouse, Movement Disorder Society Annual meeting, 2008
869. Kitazawa S., Endo Y., Yamane M., Takahashi M., Temporo-spatial gaze patterns in autistic children, 38th Annual Meeting, Society for Neuroscience, 2008
870. G. Oyama, K. Yoshimi, S. Natori, Y. Chikaoka, Y. Shimo, S. Kitazawa, R. Takahashi, N. Hattori, Reduced dopamine release in the striatum of Parkin knockout mouse, 38th Annual Meeting, Society for Neuroscience, 2008
871. Shihoko Natori, Kenji Yoshimi, Genko Oyama, Yasushi Shimo, Nobutaka Hattori, Shigeru Kitazawa, Reward-associated dopamine release in the striatum of behaving mice, 38th Annual Meeting, Society for Neuroscience, 2008
872. Shihoko Natori, Kenji Yoshimi, Maki Kagohashi, Genko Oyama, Yasushi Shimo, Nobutaka Hattori, Shigeru Kitazawa, Reward-associated dopamine release in the striatum of behaving mice, 第31回神経科学学会, 2008
873. Kitazawa S. & Nishida S., Adaptive anomalies in conscious time perception, Tutorial workshop in the 12th Annual Meeting of the Association for the Scientific Study of Consciousness, 2008
874. Juan Carlos Toledo Sales, Hiroshi Iwasaki, Eiichi Jodo, Markus H. Schmidt, Akhiro Kawachi, Tsumeharu Miki, Yukihiko Kayama, Manabu Otsuki, Yoshimasa Koyama, Penile erection and micturition events triggered by electrical stimulation of the mesopontine tegmental area, American Journal of Physiology, 292, R102-R111, 2008
875. Gulia KK, Jodo E, Kawachi A, Miki T, Kayama Y, Mallick HN, Koyama Y, The septal area, site for the central regulation of penile erection during waking and REM sleep in rats: a strianulation study, Neuroscience, 156, 4, 1064-1073, 2008
876. Motomura W, Yoshizaki T, Ohtani K, Okumura T, Fukuda M, Fukuzawa J, Mori K, Jang S-J, Nomura N, Yoshida I, Suzuki Y, Kohgo Y, Wakamiya N, Tissue distribution of a collectin CL-K1 in murine tissues, J.Histchem Cytochem, 56, 243-252, 2008
877. Yamazaki M., Nakamura K., Mizukami Y., Ii M., Sasajima J., Sugiyama Y., Nishikawa T., Nakano Y., Yanagawa N., Sato K., Maemoto A., Tanno S., Okumura T., Karasaki H., Kono T., Fujii Y., Ashida T., Chung DC., Kohgo Y., Sonic hedgehog derived from human pancreatic cancer cells augments angiogenic function of endothelial progenitor cells, Cancer Sci, 99, 1131-1138, 2008
878. Tanno S., Nakano Y., Nishikawa T., Nakamura K., Sasajima J., Minoguchi M., Mizukami Y., Yanagawa N., Fujii T., Obara T., Okumura T., Kohgo Y., Natural History of Branch Duct Intraductal Papillary-Mucinous Neoplasms of the Pancreas without Mural Nodules: Long-term Follow-up Results, Gut, 57, 339-343, 2008
879. Okumura T., Takakusaki K., Role of orexin in central regulation of gastrointestinal functions, J Gastroenterol, 43, 652-660, 2008
880. Kumei S., Motomura W., Yoshizaki T., Takakusaki K., Okumura T., Troglitazone increases expression of E-cadherin and claudin 4 in human pancreatic cancer cells, Biochem Biophys Res Commun (in press)
881. Ogihara N., Makishima, H., Aoi, S., Sugimoto, Y., Tsuchiya, K., Nakatsukasa, M., Development of an Anatomically Based Whole-Body Musculoskeletal Model of the Japanese Macaque (*Macaca fuscata*), American Journal of Physical Anthropology, in press
882. Aoi, S., Ogihara, N., Sugimoto, Y., Tsuchiya, K., Simulating adaptive human bipedal locomotion based on phase resetting using foot-contact information, Advanced Robotics, 22, 1697-1713, 2008
883. Oishi, M., Ogihara, N., Endo, H., Asari, M., Muscle architecture of the upper limb in the orangutan, Primates, 49, 204-209, 2008
884. Kagaya, M., Ogihara, N., Nakatsukasa, M., Morphological study of the anthropoid thoracic cage: scaling of thoracic width and analysis of rib curvature, Primates, 49, 89-99, 2008
885. S. Aoi, Y. Sato, and K. Tsuchiya, Arc Fes Effects on Stability Based on a Simple Oscillator-Driven Walking Model, Journal of Robotics and Mechatronics, 20, 5, 709-718, 2008
886. Yasuhiro Sugimoto, Koichi Osaka, Hierarchical Implicit Feedback Structure in Passive Dynamic Walking, Journal of Robotics and Mechatronics, 20, 4, 559-566, 2008
887. Yasuhiro Sugimoto, Shinya Aoi, Naomichi Ogihara, Kazuo Tsuchiya, The Stabilizing function of musculoskeletal system for periodic motion, Advanced Robotics, in press
888. Kazuhiko Nakatani, Yasuhiro Sugimoto, Koichi Osaka, Demonstration and Analysis of Quadrupedal Passive Dynamic Walking, Advanced Robotics, in press
889. Ogihara, N., Aoi, S., Sugimoto, Y., Nakatsukasa, M., Tsuchiya, K., Computer simulation of locomotion in the Japanese monkey: A constructive approach towards understanding adaptive mechanism in primate locomotion, IEEE/RSJ 2008 International Conference on Intelligent Robots and Systems Workshop, Nice, France, 2008
890. Ogihara, N., Nakatsukasa, M., A computer simulation study of precision grip in human and chimpanzee based on an anatomically realistic hand musculoskeletal model, IPS Post-Congress Symposium on Comparative Functional Morphology in Primates, Durham, UK, 2008
891. Kagaya, M., Ogihara, N., Nakatsukasa, M., Clavicular length of hominoids: a comparison with the thoracic cage width, IPS Post-Congress Symposium on Comparative Functional Morphology in Primates, Durham, UK, 2008
892. Ogihara, N., Hirasaki, E., Nakatsukasa, M., Experimental and computational studies of bipedal locomotion in the bipedally-trained Japanese monkey, The International Primatological Society XXII Congress, Edinburgh, UK, 2008
893. Kagaya, M., Ogihara, N., Nakatsukasa, M., Morphological Study of the anthropoid thoracic cage: Rib orientation and its implication for orthograde postural behavior, The International Primatological Society XXII Congress, Edinburgh, UK, 2008
894. Ogihara, N., Aoi, S., Sugimoto, Y., Nakatsukasa, M., Tsuchiya, K., Synthetic study of quadrupedal/bipedal locomotion in the Japanese monkey, 4th International Symposium on Adaptive Motions of Animals and Machines, Cleveland, OH, USA, 2008
895. S. Aoi, N. Ogihara, Y. Sugimoto, and K. Tsuchiya, Computer Simulation of Adaptive Human Bipedal Locomotion Based on Phase Resetting Using Foot Contact Information, 4th Int. Symp. on Adaptive Motion of Animals and Machines, 64-65, 2008
896. S. Aoi, Y. Sato, and K. Tsuchiya, Stability Characteristics in Walking Behavior with Two Different Oscillatory Elements: Roles of Arc Foot and Internal Oscillator, Proc. IEEE/RSJ Int. Conf. on Intell. Robot. Syst., 3414-3419, 2008
897. Y. Sugimoto, S. Aoi, N. Ogihara, K. Tsuchiya, The role of the force-velocity relationship of muscle for the stability of periodic motions, 4th Int. Symp. on Adaptive Motion of Animals and Machines, 2008
898. K. Hosoda, T. Takama, A. Nakamoto, S. Hayashi, Biped Robot Design Powered by Antagonistic Pneumatic Actuators for Multi-Modal Locomotion, Robotics and Autonomous Systems, 56, 1, 46-53, 2008
899. K. Tsujita, T. Kohyashi and T. Masuda, A Feasibility Study on Stability of Gait Patterns with Changeable Body Stiffness using Pneumatic Actuators in Quadruped Robot, Advanced Robotics, 23, 5, to appear, 2009
900. K. Tsujita, T. Ihnora, T. Kohyashi and T. Masuda, A Study on Locomotion Stability by Controlling Joint Stiffness of Biped Robot with Pneumatic Actuators, Motion and Vibration Control, 305-314, 2008
901. T. Takama, S. Hayashi, K. Hosoda, 3D Biped Robot for Multi-modal Locomotion Driven by Antagonistic Pneumatic Actuators, Fourth International Symposium on Adaptive Motion of Animals and Machines, CD-ROM, 2008
902. Koh Hosoda, Hiroshi Takayama, and Takashi Takama, Jumping of an Anthropomorphic Robot Equipped with Bifurcated Muscles, Fourth International Symposium on Adaptive Motion of Animals and Machines, CD-ROM, 2008
903. T. Takama, S. Hayashi, K. Hosoda, 3D Bipedal Robot with Tunable Leg Compliance Mechanism for Multi-modal Locomotion, IEEE/RSJ 2008 International Conference on Intelligent Robots and Systems, 1097-1102, 2008
904. K. Hosoda, H. Takayama, T. Takama, Bouncing Monopod with Bio-mimetic Muscular-Skeleton System, IEEE/RSJ

- 2008 International Conference on Intelligent Robots and Systems, 3083-3088, 2008
905. K.Tsujita, T.Kobayashi, T.Irouma and T.Masuda, Gait Transition by Tuning Muscle Tones using Pneumatic Actuators in Quadruped Locomotion, Proc. of IEEE/RSJ IROS2008, 2453-2458, 2008
906. K.Tsujita, T.Irouma, T.Kobayashi and T.Masuda, A Study on Locomotion Stability by Controlling Joint Stiffness of Biped Robot with Pneumatic Actuators, CD-ROM Proc. of Int. Conf. of Motion and Vibration Control, ROI-1195, 2008
907. K.Tsujita, T.Kobayashi, T.Irouma and T.Masuda, A study on adaptive gait transition of quadruped locomotion by changing muscle tone, Proc. of SICE Annual Conference 2008, 2489-2494, 2008
908. K.Tsujita, T.Irouma, T.Kobayashi and T.Masuda, A Study on Locomotion Stability at the Variance of Joint Stiffness, Proc. of Int. Symp. on Adaptive Motion of Animals and Machines (AMAM) 2008, 58-59, 2008
909. C. Mautroy, H. Kimura and K. Takase, Towards a general neural controller for quadrupedal locomotion, NEURAL NETWORKS, 21, 4, 667-681, 2008
910. C. Mautroy, H. Kimura and K. Takase, Towards a general neural controller for 3D quadrupedal locomotion, Proc. of SICE Annual Conference 2008, 2495-2500, 2008
911. T. Masuda, H. Kimura and K. Takase, Emergence of a Quadruped Bound Gait as Interaction among the Brain, Body and Environment, Proc. of SICE Annual Conference 2008, 2501-2506, 2008
912. Y. Oda, H. Kimura and K. Takase, Adaptive Walking of a 2D Biped Robot during Splitbelt Treadmill, Proc. of SICE Annual Conference 2008, 2507-2512, 2008
913. H. Kimura, Robotics as a Tool for Gait AND Posture Study, Fourth International Symposium on Adaptive Motion of Animals and Machines, CD-ROM, 2008
914. C. Mautroy and H. Kimura, Towards a general neural controller for 3D quadrupedal locomotion, Proc. of 20th Autonomous Distributed System Symposium, 251-256, 2008
915. K. Nakamura, W. Yoshinaga, Kinoue, Development of a Biomimetic control system for a Snake-like Robot with Pneumatic Actuators, 4th International Student Conference at Ibaraki University, 66-72, 2008
916. Yoshinori Izaki, Masatoshi Takita and Tatsuo Akema, Specific role of the posterior dorsal hippocampus-prefrontal cortex in short-term working memory, European Journal of Neuroscience, 27, 3029-3034, 2008
917. Takeshi Uejima, Toshiyuki Fujii, Hiroshi Yokoi, Masatoshi Takita, Motion Classification by Epidural Potential Measurement of Rat for Low-Invasive Brain-Machine Interface, Proceedings of 2008 IEEE International Conference of Robotics and Biomimetics, 2009
918. Kojiro Matsushita, Hiroshi Yokoi, and Tamio Arai, Robotic Education for Human-Robot Interaction: Proposal of Two Robot Developmental Kits that Bring Creativity, 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Workshop Teaching Human-Robot Interaction to Humans, 2008
919. Hiroshi Yokoi and Kojiro Matsushita, Self-regulatory Hardware: Evolutionary Design for Mechanical Passivity on a Pseudo Passive Dynamic Walker, Artificial Life Models in Hardware (Ed. Andrew Adamatzky and Maciej Komosinski), Springer-Verlag, 2009
920. Kojiro Matsushita and Hiroshi Yokoi, Embodiment of Legged Robots Emerged in Evolutionary Design: Pseudo Passive Dynamic Walker, Frontiers in Evolutionary Robotics (Ed. Aleksandar Lazinica), I-Tech Education and Publishing, ISBN: 978-3-902613-19-6, 311-326, 2008
921. Naoki Kotaka, Takafumi Suzuki, Kunihiro Mabuchi, Shoji Takeuchi, A flexible polyene neural probe combined with a microdialysis membrane, Proc. of microTAS 2008, 1687-1689, 2008
922. Osamu Fukayama, Noriyuki Taniguchi, Takafumi Suzuki, Kunihiro Mabuchi, Automatic Adaptation of Vehicle Controller to Time-Varying Neural Signals Recorded in Rat-Car System: A Vehicle-formed BMI, Proc. of Joint 4th International Conference on Soft Computing and Intelligent Systems and 9th International Symposium on Advanced Intelligent Systems, 253-256, 2008
923. Osamu Fukayama, Noriyuki Taniguchi, Takafumi Suzuki, Kunihiro Mabuchi, Rat-Car system for estimating locomotion states using neural signals with parameter monitoring: Vehicle-formed brain-machine interfaces for rat, Proc. of 30th Annual International Conference of the IEEE EMBS, 5322-5325, 2008
924. Takafumi Suzuki, Development of flexible neural probes and their applications to neuroprostheses, EDIS 2008 satellite symposium GCOE global seminar Advances in Neuroengineering, 2008
925. Noriyuki Taniguchi, Osamu Fukayama, Tatsuo Okubo, Takafumi Suzuki, Kunihiro Mabuchi, Rat-Car System: A vehicle-formed BMI system by neural signals recorded with implantable electrodes, Proc. of International Symposium on Biological and Physiological Engineering, 173-174, 2008
926. Sakurai, Y., Takahashi, S., Dynamic synchrony of focal cell assembly, Reviews in the Neuroscience, 16, In press, 2008
927. Hirokawa, J., Bosch, M., Sakata, S., Sakurai, Y. and Yamamori, T., Functional role of the secondary visual cortex in multisensory facilitation in rats, Neuroscience, 153, 1402-1417, 2008
928. Takahashi, S., Sakurai, Y., Hippocampal neuronal ensembles act as comparator during delayed non-matching to sample performance in rats, 38th Society for Neuroscience Annual Meeting, .
929. Hirokawa, J., Sadaikane, O., Sakata, S., Bosch, M., Sakurai, Y., Yamamori, T., Superior colliculus differently mediates behavioral facilitations of speed and accuracy by audiovisual integration, 38th Society for Neuroscience Annual Meeting, . USA, Nov, 2008
930. Yasushi Kobayashi, Ken-ichi Okada, Different Pedunculopontine Tegmental Neurons Signal Predicted and Actual Task Rewards, The XXV Barany Society Meeting, Satellite symposium, Neural mechanism in control of eye, head and limb movements, P11, 2008
931. Yasushi Kobayashi, Pedunculopontine Tegmental Nucleus Neurons Signal Predicted and Actual Reward for Reinforcement Learning, 12th Annual meeting, Association for the Scientific Study of Consciousness, 121, 2008
932. Yasushi Kobayashi, Motivation and reward prediction error computation in the midbrain, Open Problems in Neuroscience of Decision Making OIST symposium, 2008
933. Ken-ichi Okada, Yasushi Kobayashi, Neural correlates of task performance of the visually guided saccade tasks in the primate pedunculopontine tegmental nucleus, Society for Neuroscience Abstract, 88.8, 2008
934. Ken-ichi Okada, Yasushi Kobayashi, Neural correlates of task performance in the primate pedunculopontine tegmental nucleus, Neuroscience Research, 61, Suppl 1, S60, 2008
935. Yui Kitamura, Koshiro Maruyama, Ken-ichi Okada, Yasushi Kobayashi, Yuji Yahata, Syoji Kobashi, Ikuko Mohri, Masako Tanike, Using eye-movements as a research tool in children with autistic spectrum disorders, Neuroscience Research, 61, Suppl 1, S131, 2008
936. Tomohiko Takei, Kazuhiko Seki, Spinomuscular coherence in monkey performing a precision grip task, Journal of Neurophysiology, 99, 4, 2012-2020, 2008
937. Kazuhiko Seki, Tomohiko Takei, Activity of spinal interneurons mediating afferent inputs from forearm muscles in monkeys performing voluntary wrist movement, The 38th annual meeting of the Society for the Neuroscience, 86020, 2008
938. Jackson, A., Baker, SN, Ito, T., Seki, K., Motor networks in the primate cervical spinal cord explored using intraspinal microstimulation, The 38th annual meeting of the Society for the Neuroscience, 86019, 2008
939. Tomohiko Takei, Kazuhiko Seki, Spinomuscular coherence in monkey performing a precision grip task, The 38th annual meeting of the Society for the Neuroscience, 7717, 2008
940. Chiken S, Shashidharan P, Nambu A, Cortically evoked long-lasting inhibition of pallidal neurons in a transgenic mouse model of dystonia, Journal of Neuroscience, 28, 51, 13967-13977, 2008
941. Tachibana Y, Kita H, Chiken S, Takada M, Nambu A, Motor cortical control of internal pallidal activity through glutamatergic and GABAergic inputs in awake monkeys, European Journal of Neuroscience, 27, 1, 238-253, 2008
942. Hatanaka N, Tokuno H, Nambu A, Takada M, Transcranial doppler ultrasonography monitors cerebral blood flow changes in relation to motor tasks, Cerebral Cortex, in press, 2009
943. Nambu A, Seven problems on the basal ganglia, Current Opinion in Neurobiology, 18, in press, 2008
944. Nambu A, Basal ganglia: physiological circuits, Encyclopedia of Neuroscience, 2, 111-117, 2009
945. S. Tomatsu, Y. Someya, Y.W. Sung, S. Ogawa S., S. Kakei, Temporal features of BOLD responses varies with temporal patterns of movement, Neurosci Res, 62, 160-167, 2008
946. Y. Tsunoda, S. Kakei, Reaction time changes with the hazard rate for a behaviorally relevant event when monkeys perform a delayed wrist movement task, Neurosci Lett, 433, 152-157, 2008
947. J.H. Lee, Y. Kagamiyama, S. Kakei, Quantitative Evaluation of Movement Disorders in Neurological Diseases based on EMG Signals, Conf Proc IEEE Eng Med Biol Soc, 1, 181-184, 2008
948. J.H. Lee, Y. Kagamiyama, S. Kakei, Quantitative Evaluation of Cerebellar Ataxia based on EMG signals, The second IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechanics, in press, in press, 2009
949. J.A. Ting, A. D'Souza, K. Yamamoto, T. Yoshioka, D.S. Hoffman DS, S. Kakei, Variational Bayesian least squares: An application to brain-machine interface data, Neural Netw, 21, 1121-1131, 2008
950. S. Kakei, Cerebellar mossy fibers provide precise copies of cortical motor commands, XXV Barany Society Meeting, Kyoto, April 2008, 2008
951. S. Kakei, Gain modulation and wrist motor control: from agonist selection to sensorimotor transformation, Neuroscience Seminar, Johns Hopkins University, Baltimore MD, Nov 2008, 2008
952. S. Tomatsu, Y. Tsunoda, S. Kakei, Temporal patterns of Golgi cell activities for execution of wrist movements in monkeys, 38th Annual Meeting of the Society for Neuroscience, Washington DC, Nov, 2008
953. Y. Tsunoda, S. Kakei, Reaction time reflects anticipation of events in a simple reaction time task in the monkey, 38th Annual Meeting of the Society for Neuroscience, Washington DC, Nov, 2008
954. Hanakawa T, Dimyan MA, Hallett M, The representation of blinking movement in circulate motor areas: a functional magnetic resonance imaging study, Cerebral Cortex, 18, 4, 930-937, 2008
955. Iseki K, Hanakawa T, Shinozaki J, Nankaku M, Fukuyama H, Neural mechanisms involved in observation and imagery of gait movement, Neuroimage, 41, 3, 1021-1031, 2008
956. Hanakawa T, Dimyan MA, Hallett M, Motor planning, imagery and execution: a time-course study with functional MRI, Cerebral Cortex, 18, 12, 2775-2788, 2008
957. Namiki C, Yamada M, Yoshida H, Hanakawa T, Fukuyama H, Murai T, High resolution MRI revealed small orbitofrontal traumatic lesions responsible for behavioral changes, Neurocase, 14, 6, 474-479, 2008
958. Yamamoto T, Takahashi S, Hanakawa T, Urayama S, Fukuyama H, Ejima Y, The stereokinetic effect reveals different roles of the lateral occipito-temporal and parietal cortex for 3-D perception from motion: An fMRI study, Journal of Vision, 8, 10:14, 1-17, 2008
959. Lerner A, Bagci A, Hanakawa T, Boudreau EA, Pagan F, Mari Z, Bani-Jimenez W, Aksu M, Sato S, Murphy DL, Hallett M, Is the insula responsible for suppression of natural urges?, Cerebral Cortex, 19, 1, 218-223, 2009
960. Matsumoto R, Okada T, Mikuni N, Mitsuoka T, Taki J, Sawamoto N, Hanakawa T, Miki Y, Ikeda A, Hashimoto N, Fukuyama H, Takahashi R, Hemispheric asymmetry of the arcuate fasciculus in patients with unilateral language dominance defined by Wada test, Journal of Neurology, 255, 11, 1703-11, 2008
961. Tsubomi H, Ikeda T, Hanakawa T, Hirose N, Fukuyama H, Osaka N, Parieto-occipital connectivity predicts top-down attentional effect in visual masking: an fMRI study with individual differences approach, Neuroimage, in press
962. Toda H, Sawamoto N, Hanakawa T, Saiki H, Matsumoto S, Okamura R, M, Ishikawa M, Fukuyama H, Hashimoto N, A novel composite targeting method using high-field magnetic resonance imaging for subthalamic nucleus deep brain stimulation, Journal of Neurosurgery, in press
963. Abe M, Hanakawa T, Functional coupling underlying motor and cognitive functions of the dorsal premotor cortex, Behavioral Brain Research, 198, 1, 13-23, 2009
964. Hanakawa T, Mima T, Matsumoto R, Abe M, Inouchi M, Urayama S, Anami K, Honda M, Fukuyama H, Stimulus-response profile during single-pulse transcranial magnetic stimulation to the primary motor cortex, Cerebral Cortex, in press
965. Hanakawa T, Hallett M, Parallel basal ganglia-frontal cortical loops for the control of motor and cognitive agility, Neuroscience 2008, Online, 2008
966. Shitara H, Hanakawa T, Shinozaki T, Takagishi K, Honda M, Simultaneous measurement of fMRI, TMS and EMG with stepping stone sampling method, 14th Annual Meeting of the Organization for Human Brain Mapping, Online, 2008
967. Tanaka S, Honda M, Hanakawa T, Cohen LG, Consolidation of motor memories encoded by different practice schedules, 14th Annual Meeting of the Organization for Human Brain Mapping, Online, 2008
968. Hanakawa T, Hosoda C, Honda M, Does mental rotation of hands and feet involve somatotopically organized brain regions?, 14th Annual Meeting of the Organization for Human Brain Mapping, Online, 2008
969. Hosoda C, Hanakawa T, Nariai T, Ohno K, Honda M, Substrates of Switching of Phonology between the First and Second Languages, 14th Annual Meeting of the Organization for Human Brain Mapping, Online, 2008
970. Matsumoto R, Sawamoto N, Urayama S, Mikuni N, Hanakawa T, Behrens T, Ikeda A, Takahashi R, Fukuyama H, In vivo tract tracing of cortico-cortical connections in humans: a combined study of CCEP and probabilistic diffusion tractography, 14th Annual Meeting of the Organization for Human Brain Mapping, Online, 2008
971. Ashikaga M, Sakura M, Kikuchi M, Hiraguchi T, Chiba R, Aonuma H, and Ota J, Establishment of social status without individual discrimination in the cricket, Adv. Robotics, in press, 2009
972. Aonuma H, Kitamura Y, Niwa K, Ogawa H, and Oka K, Nitric oxide-cGMP signaling in the local circuit of the cricket abdominal nervous system, Neuroscience, 157, 749-761, 2008
973. Okada R, Ikeno H, Aonuma H, and Ito E, Biological insights into robotics: Honeybee foraging behavior by waggle dance, Adv. Robotics, 22, 1665-1681, 2008
974. Ishikawa Y, Aonuma H, and Miura T, Soldier-specific modification of the mandibular motor neurons in termites, PLoS ONE, 3, 7, e2617:1-8, 2008
975. Yono O, and Aonuma H, Cholinergic neurotransmission from mechanosensory afferents to giant interneurons in the terminal abdominal ganglion of the cricket, Gryllus bimaculatus, Zool. Sci., 25, 517-525, 2008
976. Funato T, Kurabayashi D., Nara M, and Aonuma H, Switching mechanism of sensor-motor coordination through oscillator network model, IEEE Trans. Systems, Man and Cybernetics - Part B, 38, 3, 764-770, 2008
977. Okada R, Ikeno H, Sasayama N, Aonuma H, Kurabayashi D., and Ito E, The dance of the honeybee: how do they dance to transfer the food information effectively?, Acta Biol. Hung., 59, 157-162, 2008
978. Sakura M, Hiraguchi T, Ohkawara K., and Aonuma H, The Compartment structures of the antennal lobe in the ant *Aphaenogaster smaragdina japonica*, Acta Biol. Hung., 59, 183-187, 2008
979. Ikeno H, Kanzaki R, Aonuma H, Takahata M, Mizunami M, Yasuyama K, Matsui N, Yokohari F, and Usui S, Development of invertebrate brain platform: Management of research resources for invertebrate neuroscience and neuroethology, Proceedings of 14th International Conference on Neural Information Processing 2007: Part II, LNCS 4985, (Eds. Ishikawa M et al.) Springer-Verlag Berlin Heidelberg, 905-914, 2008
980. Aonuma H, Modelling of social interaction dependent behavior selection in the cricket, Workshop on Dynamical Circuits in the Brain, 2008
981. Ota J, Aonuma H, Asama H, Kawabata K, and Ashikaga M, Multidisciplinary contributions from neuroethology and engineering-Understanding experience dependent behavior selection in crickets, IROS2008, 54-59, 2008
982. Aonuma H, Experience dependent behavior selection in the cricket, International Seminar: Evolutionary Studies in Behavioral Neuroscience, 2008
983. Aonuma H, and Ota J, Synthetic neuroethological approach to understand experience dependent adaptive behavior in the cricket, The 4th International Symposium on Adaptive Motion of Animals and Machines, 2008
984. Aonuma H, Murakami J, and Nagao T, Nitric oxide mediated biogenic amine system underlying agonistic behavior in the crickets, FENS2008, 2008
985. Ashikaga M, Sakura M, Kikuchi M, Hiraguchi T, Chiba R, Ota J, and Aonuma H, Modeling of adaptive behavior of crickets in crowd, FENS2008, 2008
986. K. Kawabata, T. Fujiki, T. Fujii, H. Aonuma, Y. Ikemoto, M. Ashikaga, J. Ota, T. Suzuki, H. Asama, Towards Synthetic Understanding of Neural System of Adaptive Behavior Selection in the Fighting Behavior of Male Crickets, 6th Forum of European Neuroscience Abstr, 4, 2267, 2008
987. Aonuma H, Modelling of experience dependent behavior - Fighting among male crickets, International Conference for Nonlinear Sciences SAPPORO WINTER SCHOOL, 2009
988. Norisuke Fujii and Jun Ota, Reassignment Task by Multiple Mobile Robots with Efficient Calculation of Task Constraints, Advanced Robotics, 22, 2-3, 191-213, 2008
989. Kenji Tenbayashi, Natsuki Miyata and Jun Ota, Grasp Strategy when Experiencing Hands of Various Sizes, International Journal on Human-Computer Interaction, 1, 4, 55-74, 2008
990. K. Nakajima, S. Morishita, T. Kazawa, R. Kanzaki, K. Kawabata, H. Asama, T. Mishima, Interpolation of binarized CLSM images for extraction of premotor neuron branch structures in silkworm moth, Sensor Review, in printing, 2008
991. Yusuke Ikemoto, Shingo Suzuki, Hiroyuki Okamoto, Hiroki Murakami, Hajime Asama, Soichiro Morishita, Takatoshi Mishima, Xin Lin, Hideo Itoh, Force sensor system for structural health monitoring using passive RFID tags, Sensor Review, in printing, 2009
992. J. Ota, H. Aonuma, H. Asama, K. Kawabata, Modeling of Adaptive Mechanism in Crickets by Means of Constructive Approach, Workshop/Tutorial Proceedings of International Conference on Intelligent Robots and Systems, 5, 988-991, 2008
993. Yewguan Soo, Masao Sugi, Hiroshi Yokoi, Tamio Arai, Tatsuhiko Nakamura, Rulin Du and Jun Ota, The Relationship between Changes in Amplitude and Instantaneous Mean Frequency at Low and High Frequency Bands during Dynamic Contraction, Proceedings of the 2nd Int. Conference on Bioinformatics and Biomedical Engineering, 02:06:04, 1-4, 2008
994. Yewguan Soo, Masao Sugi, Hiroshi Yokoi, Tamio Arai, Rulin Du and Jun Ota, Simultaneous Measurement of Force and Muscle Fatigue using Frequency-band Wavelet Analysis, Proceedings of 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 5045-5048, 2008

995. Hitoshi Aonuma, Modori Sakura, Mika Kikuchi, Masatoshi Ashikaga and Jun Ota, Synthetic neuroethological approach of understanding neuronal mechanisms of social adaptive behavior of crickets, Prepr. 10th RIES-Hokudai International Symposium on aya, 71-72, 2008
996. M. Otake, T. Takagi, H. Asama, Open Brain Simulator Estimating Internal State of Human through External Observation towards Human Biomechanics, Proc. 2008 IEEE International Conference on Robotics and Automation, 2008
997. M. Murabayashi, Y. Ikemoto, M. Otake, T. Maeda, M. Kato, H. Asama, Analysis of the Sense of Agency using a Tactile Device, 17th CISM-HIToMMS Symposium on Robot Design, Dynamics, and Control, 2008
998. Y. Ikemoto, S. Suzuki, H. Okamoto, H. Murakami, X. Lin, H. Itoh, H. Asama, Monitoring using Passive RFID Tags for Structural Health Monitoring, 2nd IEEE International Interdisciplinary Conference on Portable Information Devices, 2008
999. M. Ikeda, Y. Ikemoto, T. Miura, H. Asama, A Termite Internal State Model for Elucidating Caste Differentiation, 2008 SICE Annual Conference, 142-145, 2008
1000. K. Nakajima, S. Morishita, T. Kazawa, R. Kanzaki, H. Asama, T. Mishima, Interpolation of the Cross-sectional Area of a Premotor Neuron in a Silkworm Moth Brain using the Ellipse Model, 2008 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems, 2008
1001. S. Yano, Y. Ikemoto, H. Aonuma, T. Nagao, H. Asama, Modeling of self-organized competition hierarchy with body weight development in larval cricket, *Gryllus bimaculatus*, Preprints 9th International Symposium on Distributed Autonomous Robotic Systems, 2008
1002. Q. An, Y. Ikemoto, H. Asama, H. Matsukawa, D. Chugo, K. Takakusaki, Extraction of Behavior Primitives in Human Standing-Up Motion for Development of Power Assisting Machine, 2008 IEEE International Conference on Robotics and Biomimetics, 2009
1003. Tetsuro Funato, Daisuke Kurabayashi, Network Structure for Control of Coupled Multiple Non-Linear Oscillators, IEEE Transactions on Systems, Man and Cybernetics - Part B, 38, 3, 675-681, 2008
1004. Herianto, Toshiki Sakakibara, Tomoki Koiva, Daisuke Kurabayashi, Realization of Pheromone Potential Field for Autonomous Navigation by Radio Frequency Identification, Advanced Robotics, 22, 1461-1478, 2008
1005. Tomoki Kazawa, Hidetoshi Ikero, Ryohei Kanzaki, Development and application of a neuroinformatics environment for neuroscience and neuroethology, Neural Networks, 21, 8, 1047-1055, 2008
1006. Kanako Nakajima, Taketoshi Mishima, Soichiro Morishita, Hajime Asama, Tomoki Kazawa, Ryohei Kanzaki, Kuniaki Kawabata, Interpolation of binarized images for form reconstruction of a neuron, Sensor Review, in press
1007. Tomoko Yamagata, Takeshi Sakurai, Keiro Uchino, Hideki Sezutsu, Toshiki Tamura, Ryohei Kanzaki, GFP labeling of neurosecretory cells with the GAL4/UAS system in the silkworm brain enables selective intracellular staining of neurons, Zoological Science, 25, 5, 509-516, 2008
1008. Shigehiro Namiki, Ryohei Kanzaki, Reconstructing the population activity of olfactory output neurons that innervate identifiable processing units, Frontiers in Neural Circuits 21, 2, 1, 1-11, 2008
1009. Shigehiro Namiki, Satoshi Iwabuchi, Ryohei Kanzaki, Representation of a mixture of pheromone and host plant odor by antennal lobe interneurons of the silkworm *Bombyx mori*, Journal of Comparative Physiology A, 194, 501-515, 2008
1010. Tomoki Kazawa, Shigehiro Namiki, Ryota Fukushima, Mitsuhiro Terada, Kajin Soo, Ryohei Kanzaki, Constancy and variability of glomerular organization in the antennal lobe of the silkworm, Cell and Tissue Research, accepted, accepted
1011. Ryota Fukushima, Ryohei Kanzaki, Modular subdivision of mushroom bodies by kenyon cells in the silkworm, Journal of Comparative Neurology, 513, 315-330, 2008
1012. Masaki Iwano, Evan S. Hill, Akio Mori, Tatsuya Mishima, Tsuneko Kumagai, Kei Ito, Ryohei Kanzaki, Generation mechanism of flip-flop activity in the lateral accessory lobe and ventral protocerebrum of the insect brain, Journal of Comparative Neurology, accepted
1013. Ryohei Kanzaki, Noriyasu Ando, Takeshi Sakurai, Tomoki Kazawa, Understanding and reconstruction of the mobility of insects employing multiscale biological approaches and robotics, Advanced Robotics, 22, 1605-1628, 2008
1014. Takuro Moriyama and Daisuke Kurabayashi, An Oscillator Network with a Temporary Memory Function, IEEE International Conference on Robotics and Biomimetics (accepted, to be appeared), 2009
1015. Daisuke Kurabayashi, Tatsuki Choh, Ja Cheng, Tetsuro Funato, Adaptive Formation Transition among a Mobile Robot Group based on Phase Gradient, IEEE International Conference on Robotics and Biomimetics (accepted, to be appeared), 2009
1016. Herianto, Toshiki Sakakibara, Daisuke Kurabayashi, Realization of an Artificial Pheromone System by using Random Data Carriers for Navigation of Autonomous Robots, 5th International Conference on Ubiquitous Robots and Ambient Intelligence, 329-334, 2008
1017. Ryohei Kanzaki, Insect-Machine Hybrid System for Understanding and Evaluating the Motor Control by Sex Pheromone in *Bombyx mori*, Janelia Farm Conference, 2008
1018. Ryohei Kanzaki, Insect-Machine Hybrid System for Understanding an Adaptive behavior, The 10th International Conference on the Simulation of Adaptive Behavior (SAB08), 2008
1019. Kamiura N, Urata H, Saitoh A, Isokawa T, Ikero H, Matsui N, Seki Y, Kanzaki R, On-map based classification of insect neurons using three-dimensional quantification, SMC 2008, 2008
1020. Nakajima K, Asama H, Kanzaki R, Mishima T, Interpolation of the cross-sectional surface of a single neuron using the ellipse model, IAS10, 2008
1021. Kurabayashi D, Kanzaki R, Minegishi R, Takashima A, Tonihara S, Bio-machine fusion system: novel synthetic methodology to investigate adaptive behaviors of insects, IROS Workshop, 2008
1022. Noriyasu Ando, Shuhei Ermoto, Hirokazu Takahashi, Ryohei Kanzaki, Adaptability of pheromone tracking behavior of the silkworm revealed by the insect-controlled robot, AMAM 2008 conference abstract, 60-61, 2008
1023. Ryo Minegishi, Shigeru Tonihara, Daisuke Kurabayashi, Ryohei Kanzaki, Construction of a brain-machine fusion system to evaluate adaptability in an insect, AMAM 2008 conference abstract, 131-132, 2008
1024. Ryohei Kanzaki, Insect-Machine Hybrid System for Understanding an Adaptive Control in Biological Systems, AMAM 2008 conference abstract, 24-25, 2008
1025. Takeshi Sakurai, Hidefumi Mitsuno, Keiro Uchino, Hideki Sezutsu, Toshiki Tamura, Fumio Yokohari, Takeshi Nishigaki, Ryohei Kanzaki, Activation of bombykol receptor neurons by ectopically expressed olfactory receptor triggers pheromone searching behavior in male silkworms, ISOT 2008 conference abstracts, 189, 2008
1026. Ryota Fukushima, Takeshi Sakurai, Keiro Uchino, Hideki Sezutsu, Toshiki Tamura, Ryohei Kanzaki, Anatomical and functional organization of Kenyon cells in the mushroom bodies of male *Bombyx mori*, ISOT 2008 conference abstract, 95, 2008
1027. Ikuo Nishikawa, Masayoshi Nakamura, Yoshiaki Igarashi, Tomoki Kazawa, Hidetoshi Ikero, Ryohei Kanzaki, Neural network model of the lateral accessory lobe and ventral protocerebrum of *Bombyx mori* to generate the flip-flop activity, BMC Neuroscience, 9, Suppl 1, 23, 2008
1028. Suehiro Y\*, Yasuda A\*, Okuyama, Imada H, Kuroyagagi, Y, Kubo T, Takeuchi H.(2009) \*corresponding author \*equal contribution, Mass spectrometric map of neuropeptide expression and analysis of the g-protein-coupled receptor gene expression in the medaka (*Oryzias latipes*) brain, Gen. Comp. Endocrinol., in press, 2008
1029. Nakaoka T, Takeuchi H† and Kubo T. †corresponding author, Laying workers in queenless honeybee (*Apis mellifera* L.) colonies have a physiologic state similar to that of nurse bees but opposite that of foragers, J. Insect. Physiol., 54, 806-812, 2008
1030. Comette R, Koshikawa S, Miura T. Histology of the hormone-producing glands in the damp-wood termite *Hodotermopsis sjostedti* (Isoptera, Termitidae): A focus on soldier differentiation, Insectes Sociaux, 55, 2008
1031. Goto H, Comette R, Koshikawa S, Miura T. Effects of precocenes on the corpora allata and the JH tier in the damp-wood termite *Hodotermopsis sjostedti* (Isoptera: Termitidae), Sociobiology, 52, 345-356, 2008
1032. Koshikawa S, Miyazaki S, Comette R, Matsumoto T, Miura T. Genome size of termites (Insecta, Dictyoptera, Isoptera) and wood wasps (Insecta, Dictyoptera, Cryptocercidae), Naturwissenschaften, 95, 859-867, 2008
1033. Maekawa K, Mizuno S, Koshikawa S, Miura T. Compound eye development during caste differentiation of the termite *Reticulitermes speratus* (Isoptera: Rhinotermitidae), Zoological Science, 25, 699-705, 2008
1034. Comette R, Gotoh H, Koshikawa S, Miura T. Juvenile hormone tiers and caste differentiation in the damp-wood termite *Hodotermopsis sjostedti* (Isoptera, Termitidae), Journal of Insect Physiology, 54, 922-930, 2008
1035. Ishikawa A, Hongo S, Miura T. Morphological and histological examination of polyphenic wing formation in the pea aphid *Acyrthosiphon pisum* (Hemiptera, Hexapoda), Zoomorphology, 127, 121-133, 2008
1036. Fujita A, Miura T, Matsumoto T. Differences in cellulose digestive systems among castes in two termite lineages, Physiological Entomology, 33, 73-82, 2008
1037. Takeuchi H, "Analysis of Social Interactions Using Adult Medaka Fish", Common Themes and New Concepts in Sensory Formation, The 18th CDB Meeting, 2009
1038. Takeuchi H, Analysis of Social Interactions Using Adult Medaka Fish, The 54th NIBB Conference, New Frontiers for the Medaka Model, Genome, Bioresources and Biology, 2008
1039. Suehiro Y, Okuyama T, Imada H, Shimada A, Nakuru K, Takeda H, Kubo T and Takeuchi H, Modeling and molecular genetic analysis of neural mechanism for the optomotor response of the medaka fish, The 38th annual meeting of the Society for Neuroscience (Washington, DC), 2008
1040. Okuyama T, Suehiro Y, Imada H, Shimada A, Naruse K, Takeda H, Kubo T and Takeuchi H, Analysis of the molecular and neural bases that underlie sexual preference in the small Medaka fish, UCSF Neuroscience retreat (Asilomar Conference Grounds) ,2008
1041. Okuyama T, Suehiro Y, Imada H, Shimada A, Naruse K, Takeda H, Kubo T and Takeuchi H, Analysis of the molecular and neural bases that underlie sexual preference in the small Medaka fish, NASA Ames Research Center, Seminar (Lynn Rothschild Lab, NASA Ames Research Center) ,2008
1042. Okuyama T, Suehiro Y, Imada H, Shimada A, Naruse K, Takeda H, Kubo T and Takeuchi H, Modulation of Female mating receptiveness depending on visual information, using small fish medaka, Society for Neuroscience 2008 meeting (Washington D.C.) ,2008
1043. Miura T. Social evolution by gene duplication: soldier-specific lipocalin proteins and social communication in termites, Evolution 09, 67
1044. Miura T, Okamura Y, Nakagawa Y, Ishikawa A. Regulations of polyphenic wing development in the vetch aphid *Metacaca crassicauda*: morphogenesis, tradeoffs and gene expressions, Pea Aphid Genome Annotation Workshop I: Workshop Program, 32
1045. Miura T, Ishikawa A, Brisson J, Jaubert S, Rispe C, Tagu D, Walsh T. Gene annotation for the endocrinological factors in the pea aphid *Acyrthosiphon pisum*, Pea Aphid Genome Annotation Workshop I: Workshop Program, 32
1046. Okada Y, Tsuji K and Miura T, Molecular and physiological aspects of behavioral-caste differentiation in the ponerine ant *Diacamma* sp., Proceedings of 4th European Meeting of IUSSI, 166
1047. Yoshikatsu Hayashi, Mai Yuki, Ken Sugawara, Tomomori Kikuchi and Kazuki Tsuji, Analysis and modeling of ants' behavior from single to multi-body, Journal of Artificial Life and Robotics, 120-123, 2008
1048. Kikuchi T, Mizusaki S, Ohnishi S, Takahashi J, Nakajima Y, Tsuji K. Small queens and big head workers in a monomorphic ponerine ant, *Naturwissenschaften*, 95, 10, 963-968, 2008
1049. Suwabe M, Ohnishi H, Kikuchi T, Tsuji K. Seasonal and daily activity patterns of tramp and endemic ants in the northern forest of Okinawa Island, Ecological Research, doi:10.1007/s11284-008-0534-9, 2008
1050. Kikuchi T, Nakagawa T, Tsuji K. Changes in relative importance of multiple social regulatory forces with colony size in the ant *Diacamma* sp. from Japan, Animal Behaviour, 76, 6, 2069-2077, 2008
1051. Dobata, S, Sasaki, T, Mori, H, Hasegawa, E, Shimoda, M, Tsuji, K. Cheater genotypes in the parthenogenetic ant *Pristomyrmex punctatus*, Proceedings of the Royal Society of London, Series B, 276, 2, 567-574, 2009
1052. Ohtsuki, H, Tsuji, K. Adaptive reproduction schedule as a cause of worker policing in social Hymenoptera: a dynamic game analysis, The American Naturalist, in press, 2009
1053. Mai Yuki, Yoshikatsu Hayashi, Ken Sugawara, Analysis and Modeling of *Diacamma* workers' Behavior Proc. of 14th Int. Symp. on Artificial Life and Robotics 2009, 2008
1054. Ei-ichi Izawa, Socio-cognitive ability of crows: an attempt cognitive neuroethology, International seminar 'Evolutionary studies in behavioural neuroscience', -, 33, 2008
1055. Ei-ichi Izawa, Chemical neuroanatomy of the crow: do they have large prefrontal cortex?, Neuroscience Research, 61, S1, S141, 2008
1056. Toshiyuki Kunihara, Motochiro Kato, Delays in seeking psychiatric care among patients with schizophrenia in Bali, Health Knowledge, Attitudes and Practices, eds by Patricia I. Edgington and Umberto V. Mastoli, Nova Biomedical Books, Nova Science Publishers, New York, 158-172, 2008
1057. Tomoko Akiyama, Motochiro Kato, Taro Muramatsu, Takaki Maeda, Tsunekatsu Hara, Haruo Kashima, Gaze-triggered orienting is reduced in chronic schizophrenia, Psychiatry Research, 158, 287-296, 2008
1058. Hidehiko Takahashi, Masato Matsura, Michihiko Koeda, Noriaki Yahata, Tetsuya Suhara, Motochiro Kato, Yoshiro Okubo, Brain activations during judgments of positive self-conscious emotion and positive basic emotion: pride and joy, Cerebral Cortex, 18, 4, 898-903, 2008
1059. Hidehiko Takahashi, Yota Fujimura, Mika Hayashi, Harumasa Takano, Motochiro Kato, Hiroshi Ito, Tetsuya Suhara, Enhanced dopamine release by nicotine in cigarette smokers: a double-blind randomized, placebo-controlled pilot study, The International Journal of Neuropsychopharmacology, 11, 413-417, 2008
1060. Ryosuke Arakawa, Hiroshi Ito, Akihito Takano, Hidehiko Takahashi, Takuya Morimoto, Takeshi Sassa, Katsuya Ohta, Motochiro Kato, Yoshiro Okubo, Tetsuya Suhara, Dose-finding study of paliperidone ER based on striatal and extrastriatal dopamine D2 receptor occupancy in patients with schizophrenia, Psychopharmacology, 197, 229-235, 2008
1061. Hidehiko Takahashi, Tomohisa Shibuya, Motochiro Kato, Masato Matsura, Michihiko Koeda, Noriaki Yahata, Tetsuya Suhara, Yoshiro Okubo, Enhanced activation in the extrastriate body area by goal-directed actions, Psychiatry and Clinical Neurosciences, 62, 214-219, 2008
1062. Hidehiko Takahashi, Motochiro Kato, Masato Matsura, Michihiko Koeda, Noriaki Yahata, Tetsuya Suhara, Yoshiro Okubo, Neural correlates of human virtue judgment, Cerebral Cortex, 18, 8, 1886-1891, 2008
1063. Mika Hayashi, Motochiro Kato, Kazuo Igarashi, Haruo Kashima, Superior fluid intelligence in children with Asperger's disorder, Brain and Cognition, 66, 306-310, 2008
1064. Sho Yagishita, Takamitsu Watanabe, Tomoki Asari, Hiroshi Ito, Motochiro Kato, Hiroo Ikehira, Iwao Kanno, Tetsuya Suhara, Hideyuki Kikyo, Role of left superior temporal gyrus during name recall process: An event-related fMRI study, NeuroImage, 41, 1142-1153, 2008
1065. Nobuyuki Matsura, Yoshiyuki Shibukawa, Motochiro Kato, Tatsuya Ichinohe, Takashi Suzuki and Yuzuru Kaneko, Ketamine, not fentanyl, suppresses pain-related magnetic fields associated with trigeminally innervated area following CO2 laser stimulation, Neuroscience Research, 62, 105-111, 2008
1066. Hidehiko Takahashi, Motochiro Kato, Harumasa Takano, Ryosuke Arakawa, Masaki Okamura, Tatsui Otsuka, Kodaka Fumitoshi, Mika Hayashi, Yoshiro Okubo, Hiroshi Ito, Tetsuya Suhara, Differential contributions of prefrontal and hippocampal dopamine D1 and D2 receptors in human cognitive functions, The Journal of Neuroscience, 28, 46, 12032-12038, 2008
1067. Michitaka Furuyama, Taro Muramatsu, Motochiro Kato, Differential hand-neglect following a callosal lesion, Cognitive and Behavioral Neurology, 21, 4, 246-248, 2008
1068. Akira Uno, Taeko N. Wydell, Motochiro Kato, Kanae Itoh, Fumihiko Yoshino, Cognitive Neuropsychological and Regional Cerebral Blood Flow Study of a Japanese-English Bilingual Girl with Specific Language Impairment (SLI), Cortex, 45, 154-163, 2009
1069. Hidehiko Takahashi, Motochiro Kato, Sassa Takeshi, Michihiko Koeda, Noriaki Yahata, Tetsuya Suhara, Yoshiro Okubo, Diminished activation in the extrastriate body area during observation of sport-related actions in chronic schizophrenia, Schizophrenia Bulletin (in press)
1070. Tatsuhiko Yagishi, Motochiro Kato, Kosuke Izumi, Rika Kosaki, Kaori Yago,
1071. Kazuo Tsubota, Yui Sato, Minoru Okubo, Goru Watanabe, Takao Takahashi, Kenjiro Kosaki, Adult Phenotype of Multihull-Smith Syndrome, American Journal of Medical Genetics Part A, 2008 (in press)
1072. Shoko Nozaki, Motochiro Kato, Harumasa Takano, Hiroshi Ito, Hidehiko Takahashi, Ryosuke Arakawa, Masaki Okamura, Yota Fujimura, Ryohei Matsumoto, Mihio Ota, Fumihiko Yasuno, Akihito Takano, Akihito Otsuka, Yoshiro Okubo, Haruo Kashima, and Tetsuya Suhara, Regional Dopamine Synthesis in Patients with Schizophrenia using L-[β-11C]DOPAPET, Schizophrenia Research, 2008 (in press)
1073. Hidehiko Takahashi, Motochiro Kato, Masato Matsura, Dean Mobbs, Tetsuya Suhara, Yoshiro Okubo, When your gain is my pain and your pain is my gain: Neural correlates of envy and Schadenfreude, Science (in press)
1074. K. Harano, M. Sasaki, T. Nagao, M. Sasaki, Influence of age and juvenile hormone on brain dopamine level in male honeybee (*Apis mellifera*): association with reproductive maturation, Journal of Insect Physiology, 54, 848-853, 2008
1075. K. Harano, M. Sasaki, T. Nagao, K. Sasaki, Dopamine influences locomotor activity in honeybee queens: implications for a behavioural change after mating, Physiological Entomology, 33, 395-399, 2008
1076. K. Sasaki, BIOGENIC amines and division of reproduction in social insects, Insect Physiology: New Research, (Ed.) R.P. Maes, Nova Science Publisher, Chapter 7, 2008
1077. K. Sasaki, K. Yamaesaki, K. Tsuchida, T. Nagao, Gonadotrophic effects of dopamine in isolated workers of the primitively eusocial wasp, *Polistes chinensis*, Naturwissenschaften, 96, in press, 2009
1078. Ogawa, H, Cummins, G.L, Jacobs, G.A, Oka, K, Dendritic design implements algorithm for extraction of sensory information, Journal of Neuroscience, 28, 4592-4603, 2008
1079. Aonuma, H, Kitamura, Y, Niwa, K, Ogawa, H, Oka, K, Nitric oxide-cyclic guanosine monophosphate signaling in the local circuit of the cricket abdominal nervous system, Neuroscience, 157, 749-761, 2008

1080. T.Nagao, S. Kishigami, K. Sasaki, H. Tamori, Neurohormonal control of development and motivation of instinctive behavior in male crickets, 6th Asian Biophysics Association Symposium and 27th Hong Kong Society of Neuroscience Annual Meeting, Hong Kong, PS2-29, 2008
1081. Ogawa, H., Oka, K., In vivo calcium imaging of mushroom body calyx in the tethered cricket for odor-taste conditioning, 2008 Neuroscience Meeting Planner, Washington, DC: Society for Neuroscience, Program No. 362.20, 2008
1082. Shindo, Y., Ogawa, H., Hotta, K. Oka, K., Alteration of Mg<sup>2+</sup> transport during 1-methyl-4-phenyl-pyridinium ion (MPP<sup>+</sup>) induced cell death in PC12 cells, 2008 Neuroscience Meeting Planner, Washington, DC: Society for Neuroscience, Program No. 140.16, 2008
1083. Watanabe, K., Hase, S., Shimoi, T., Ogawa, H., Hotta, K. Oka, K., Expression of cyclic AMP responsive element binding protein 1 (CREB1) in long-term memory formation in the earthworm *Eisenia fetida*, 2008 Neuroscience Meeting Planner, Washington, DC: Society for Neuroscience, Program No. 793.10, 2008
1084. Ogawa, H., Oka, K., Directional-dependent plasticity in wind sensitivity of the cricket giant interneurons, *Neuroscience Research*, 60, S1, S183, 2008
1085. Mizue Ohashi, Ryuichi Okada, Toshiyuki Kimura, Hidetoshi Ikono, Observation system for the control of the hive environment by the honeybee (*Apis mellifera*), *Behav Res Methods*, in press, 2009
1086. Kanako Aono, Ayachika Fusada, Yoriyuka Fusada, Wataru Ishii, Yuji Kanaya, Mami Komuro, Kanae Matsui, Satoru Meguro, Ayumi Miyamae, Yurie Miyamae, Yurie Miyamae, Shizuka Norita, Hiroe Nozaka, Wakana Saito, Ayumi Watanabe, Kaori Nishikata, Akira Karazawa, Yutaka Fujito, Miki Yamagishi, Takashi Abe, Masafumi Nagayama, Tatsuomi Uchida, Kazutoshi Gohara, Ken Lukowiak, Eisuro Ito, Upside-down gliding of *Lymnaea*, *Biol. Bull.*, 215, 272-279, 2008
1087. Mizue Ohashi, Hidetoshi Ikono, Toshiyuki Kimura, Tadaaki Akamatsu, Ryuichi Okada, Eisuro Ito, Control of hive environment by honeybee (*Apis mellifera*) in Japan, *Proceedings of Measuring Behavior* 2008, 243, 2008
1088. Toshiyuki Kimura, Hidetoshi Ikono, Ryuichi Okada, Eisuro Ito, A Study for identification and behavioral tracking of honeybees in the observation hive using vector quantization method, *Proceedings of Measuring Behavior* 2008, 165-166, 2008
1089. Ryuichi Okada, Foraging strategy of the honeybee colony by waggle dance, International Seminar on Current Issues in Social Insect Research-In Case of Honeybee and Ants, 2008
1090. Fujii N., Hihara S., Iriki S., Social cognition in premotor and parietal cortex, *Soc Neurosci*, 3, 3-4, 250-60, 2008
1091. Fujii N., Hihara S., Nagasaka Y., Iriki A., Social state representation in prefrontal cortex, *Soc Neurosci*, 4, 1, 73-84, 2009
1092. Y. NAGASAKA, T. NOTOYA, A. IRIKI, N. FUJII, Amygdala, anterior cingulate, and orbital frontal cortices activity in Japanese macaques while watching emotional expressions with social context, Program No. 883.2, 2008 Neuroscience Meeting Planner, Washington, DC: Society for Neuroscience, 2008, Online, 2008
1093. G. S. SANTOS, Y. NAGASAKA, K. TAKENAKA, A. IRIKI, N. FUJII, H. NAKAHARA, The frontal modulation of the prefrontal cortex, parietal cortex, and caudate activity for reward-oriented behavior, Program No. 93.11, 2008 Neuroscience Meeting Planner, Washington, DC: Society for Neuroscience, 2008, Online, 2008
1094. Masafumi Yano, Hospitality Technology: The Place of Culture Technology, (quarterly issue) *ichiko*, 101, 37-46, 2009
1095. Kaoru Takakusaki, Nozomi Tomita, Masafumi Yano, Substrates for normal gait and pathophysiology of gait disturbances with respect to the basal ganglia dysfunction, *Journal of Neurology*, 255, Suppl 4, 19-29, 2008
1096. Sakamoto K, Mushiike H, Saio N, Aihara K, Yano M, Tanji J, Discharge synchrony during the transition of behavioral-goal representations encoded by discharge rates of prefrontal neurons, *Journal Cerebral Cortex*, 18, 2036-2045, 2008
1097. Hisanori Makinae, Yoshinari Makino, Tsukasa Obara, Masahumi Yano, Specific spatio-temporal activities in the cerebral ganglion of *Incilaria frustoriferi* in response to superior and inferior tentacle nerve stimulation, *Brain Research*, 1231, 47-62, 2008
1098. Kaoru Takakusaki, Nozomi Tomita, Masafumi Yano, Substrates for execution for normal gait performance with respect to the basal ganglia function, *Proc. Of IEEE/RSJ 2008 International Conference on Intelligent Robots and Systems*, September, 22-26, 2008
1099. Yoshinari Makino, Makoto Yasuake, Yuki Naka, Haruki Miura & Masafumi Yano, A computational algorithm for odor representation using a spatiotemporal sequence, *Neuroscience* 2008, 2008
1100. Y. Yoshihara, N. Tomita, Y. Makino, M. Yano, Autonomous Control for Voluntary Movement in the Real World - Online Load Estimation and Compensation using Two Parallel Redundant Actuators -, *Tohoku University Global Brain Science 2008 Summer Retreat*, 2008
1101. Makino Y, Yasuake M, Naka Y, Miura H, Yano M, Principal characteristics in odor recognition naturally emerge from spatiotemporal coding, *NEUROSCIENCE RESEARCH* 61, S249, 2008
1102. S.Sakai, M.Miida, K.Osaka, M.Umeda, Design and control of a heavy material handling manipulator for agricultural robots, *Auton Robot, DOI 10.1007/s10514-008-9090-y*, 2008
1103. K.Ohgane, K.Ueda, Instability-induced hierarchy in bipedal locomotion, *Phys. Rev. E*, 77, 51915, 2008
1104. K.Ohgane, S.Ei, H.Mahara, Neuron phase shift adaptive to time delay in locomotor control, *Applied Mathematical Modelling*, 33, pp.797-811, 2009
1105. Akio Ishiguro, \*Masahiro Shimizu, On the Task Distribution between Control and Mechanical Systems: A Case Study with an Amoeboid Modular Robot, 50 Years of Artificial Intelligence: Essays Dedicated to the 50th Anniversary of Artificial Intelligence (Eds. M. Lungarella, F. Lida, J. Boragard, and R. Pfeifer), Springer, 144-153
1106. Masahiro Shimizu, Takuma Kato, Max Lungarella, \*Akio Ishiguro, Adaptive Modular Robots Through Heterogeneous Inter-Module Connections, *Journal of Robotics and Mechatronics*, 20, 3, 386-393
1107. Takuya Umedachi, Taichi Kitamura, \*Akio Ishiguro, An Amoeboid Locomotion That Exploits Real-Time Tunable Springs and Law of Conservation of Protoplasmic Mass, *Journal of Robotics and Mechatronics*, 20, 3, 449-455
1108. Wataru Watanabe, Toshihiro Kawakatsu, \*Akio Ishiguro, Rapid and Cheap Learning by Exploiting Biarticular Muscles - A Case Study With a Two-Dimensional Serpentine Robot, *Advanced Robotics Special Issue on Mobiligence (1)*, 22, 15, 1683-1696
1109. Masaki Nomura, Daisuke Ito, Hiroki Tamate, \*Kazutoshi Gohara, Estimation of functional connectivity that causes burst-like population activities, *FORMA*
1110. J. Nishikawa and \*K. Gohara, Automata on Fractal Sets Observed in Hybrid Dynamical Systems, *International Journal of Bifurcation and Chaos*, 18, 12
1111. J. Nishikawa and \*K. Gohara, Anomaly of fractal dimensions observed in stochastically switched systems, *Physical Review E*, 77, 036210-8
1112. Masahiro Shimizu, Takuma Kato, Max Lungarella, \*Akio Ishiguro, Adaptive Reconfiguration of a Modular Robot through Heterogeneous Inter-Module Connections, 2008 IEEE International Conference on Robotics and Automation proceedings, 3527-3532
1113. Dai Owaki, Koichi Osaka, \*Akio Ishiguro, On the Embodiment That Enables Passive Dynamic Bipedal Running, 2008 IEEE International Conference on Robotics and Automation proceedings, 341-346
1114. Takuya Umedachi, Taichi Kitamura, \*Akio Ishiguro, A Fully Decentralized Control of an Amoeboid Robot by Exploiting the Law of Conservation of Protoplasmic Mass, 2008 IEEE International Conference on Robotics and Automation proceedings, 1144-1149
1115. Wataru Watanabe, Takahide Sato, \*Akio Ishiguro, An Efficient Decentralized Learning by Exploiting Biarticular Muscles, 2008 IEEE International Conference on Robotics and Automation proceedings, 3826-3831
1116. \*Akio Ishiguro, Masatoshi Koyama, Dai Owaki, Jun Nishii, Increasing Stability of Passive Dynamic Bipedal Walking by Exploiting Hyperextension of Knee Joints, the fourth meeting of Adaptive Motion of Animals and Machines (AMAM 2008) proceedings, 164
1117. Dai Owaki, Koichi Osaka, \*Akio Ishiguro, Adaptive Gait Transition between Passive Dynamic Walking and Running, the fourth meeting of Adaptive Motion of Animals and Machines (AMAM 2008) proceedings, 160-161
1118. \*Akio Ishiguro, Understanding Mobiligence Through Amoeboid Locomotion - A Case Study with a Modular Robot -, the fourth meeting of Adaptive Motion of Animals and Machines (AMAM 2008) proceedings, 20-21
1119. Dai Owaki, Koichi Osaka, \*Akio Ishiguro, Gait Transition between Passive Dynamic Walking and Running by Changing the Body Elasticity, *SICE Annual Conference* 2008, 2513-2518
1120. \*Akio Ishiguro, Takuya Umedachi, Taichi Kitamura, Toshiyuki Nakagaki, Ryo Kobayashi, A Fully Decentralized Morphology Control of an Amoeboid Robot by Exploiting the Law of Conservation of Protoplasmic Mass, *IEEE/RSJ 2008 International Conference on Intelligent Robots and Systems*
1121. Wataru Watanabe, Takuya Umedachi and Dai Owaki, Investigation of the Design Principles for Adaptive Intelligence, *Proc. of The 1st Student Organizing International Mini-Conference on Information Electronics Systems*, 221 F5P-35
1122. D. Ito, H. Tamate, M. Nomura, T. Aoyagi, and \*K. Gohara, Immunocytochemistry in low-density culture of neurons on multielectrode arrays is effective for identification of action-potential pathways, *Proceedings of neuroscience* 2008, 104948
1123. D. Ito, H. Tamate, M. Nagayama, T. Uchida, and \*K. Gohara, Multi-agent Robot Systems as Distributed Autonomous Systems, *Proceedings of MEA Meeting* 2008, 53-54
1124. H. Tamate, D. Ito, M. Nagayama, T. Uchida, and \*K. Gohara, Analysis of neural-network dynamics using multi-electrode array, *Sup. Neuroscience Research*, 25, S86
1125. M. Nomura, D. Ito, H. Tamate, \*K. Gohara, and T. Aoyagi, Estimation of neuronal functional connectivity of cultured neuronal networks, *Sup. Neuroscience Research*, 25, S90
1126. Ono, N., Madina, D. and Ikegami, Origin of Life and Lattice Artificial Chemistry, Bridging Nonliving and Living Matter, edby S.Rasmusussen, L.Chen, N.Packard, M.Bedau, D.Deamer, P.Stadler and D.Krakauer, MIT Press, 197-212, 2008
1127. Ogaï, Y., Ikegami, T., *Microslip as a Simulated Artificial Mind*, *Adaptive Behavior*, 16, 2-3, 129-147, 2008
1128. Hiroshi C. Ito, Masakazu Shimada and Takashi Ikegami, Coevolutionary dynamics of adaptive radiation for food-web development, *Population Ecology*, 51, 65-81, 2009
1129. Hisanori Takahashi, Naoto Horibe, Masakazu Shimada, and Takashi Ikegami, Analyzing the House Fly's Exploratory Behavior with Autoregression Methods, *J. Phys. Soc. Japan*, 77, 84802, 2008
1130. Accouturier, J.-J. and Ogaï, Y. and Ikegami, Using chaos to trade-off synchronization and autonomy in a dancing robot, *Trends and Controversies, IEEE Intelligent Systems*, 23, 3, 74-85, 2008
1131. Ishii Y. and Shimada M., Competitive exclusion between contest and scramble strategists in *Callosobruchus* seed beetle modeling, *Population Ecology*, 50, 197-205, 2008
1132. Ikegami, T. and Suzuki, K., From Homeostatic to Homeodynamic Self, *BioSystems*, 91, 388-400, 2008
1133. Suzuki, K. and Ikegami, T., Shape and Self-movements in Protocell Systems, *Artificial Life*, in press, 2008
1134. Ishii Y. and Shimada M., Predator's learning and search image promoting persistence of the insect prey-predator experiment system, *Population Ecology*, in review
1135. Ikegami, T., *Artificial Life is Dead*, *International 10th Conference on Artificial Life (Keynote)*, 2008
1136. Ikegami, T., *Organizer*, Agency Workshop/Satellite workshop at SAB, 2008
1137. Ikegami, T., *Self-moving droplets as emergence of a life system*, Japan-Slovenia Seminar on Nonlinear Science, 2008
1138. Nakajima, K. and Ikegami, T., Considering the reconfiguration process of subjective temporal order by using recurrent neural networks, *International 10th Conference on Artificial Life (Keynote)*, 2008
1139. Shimada M., Rapid adaptation: the new dimension of evolutionary ecology (Opening Address), 24th Society of Population Ecology, 2008
1140. Iizuka, H. and Ikegami, T., Simulating active touch with a simple embodied agent, *International 10th Conference on Artificial Life (Keynote)*, 2008
1141. Suzuki, K. and Ikegami, T., Homeodynamics in the game of life, *International 10th Conference on Artificial Life (Keynote)*, 2008
1142. Hanczyc, M. and Ikegami, T., Chemical basis for minimal cognition, *International 10th Conference on Artificial Life (Keynote)*, 2008
1143. M. Ima, A paradox of hovering insect in two-dimensional space, *Journal of Fluid Mechanics*, 617, 207-229, 2008
1144. M. Ima and A. S. Mikhailov, Propulsion hydrodynamics of a butterfly micro-swimmer, *Europhysics Letters*, accepted, 2009
1145. M. Ima and Y. Nishihara, Unstable periodic solution controlling collision of localized convection cells in binary fluid mixture, *Physica D*, 238, 449-460, 2009
1146. Ishii, M., N. Hirai and T. Hiroawari, The occurrence of an endangered lycanid, *Zizina emelina* (de l'Orza), in the Osaka International Airport, *central Japan. Trans. Lepid. Soc. Japan, Trans. Lepid. Soc. Japan*, 59, 78-82, 2008
1147. M. Yago, N. Hirai, M. Kondo, T. Tanikawa, M. Ishii, M. Wang, M. Williams, R. Ueshima, Molecular systematics and biogeography of the genus *Zizina* (Lepidoptera: Lycaenidae), *Zootaxa*, 1746, 15-38, 2008
1148. K. Senda, M. Sawamoto, M. Kitamura, T. Obara, Towards Realization of Stable Flapping-of-Wings Flight of Butterfly, *International Symposium on Adaptive Motion in Animals and Machines*, 62-63, 2008
1149. K. Senda, M. Sawamoto, M. Kitamura, T. Obara, Effects of Flexibly Torsional Wings in Flapping-of-Wings Flight of Butterfly, *World Automation Congress*, 176, 2008
1150. M. Ima, Robustness of an insect's hovering: a transition of flapping free-flight, *ICTAM 2008*, 2008
1151. T. Aoki and T. Aoyagi, Co-evolution of phases and connection strengths in a network of phase oscillators, *Physical Review Letters*, in press
1152. T. Tanaka, T. Aoyagi, Optimal weighted networks of phase oscillators for synchronization, *Physical Review E*, 78, 4, 046210-1~10, 2008
1153. T. Tanaka, T. Kaneko, T. Aoyagi, Recurrent infomax generates cell assemblies, neuronal avalanches, and simple cell-like selectivity, *Neural Computation*, in press
1154. T. Tanaka, T. Aoyagi, Weighted scale-free networks with variable power-law exponents, *Physica D*, 237, 7, 898-907, 2008
1155. T. Aoki, K. Ota, K. Kurata, T. Aoyagi, Ordering Process of Self-Organizing Maps Improved by Asymmetric Neighborhood Function, *Cognitive Neurodynamics*, in press
1156. X. Pan, K. Sawa, I. Tsuda, M. Tsukada and M. Sakagami, Reward prediction based on stimulus categorization in primate lateral prefrontal cortex, *Nature Neurobiology*, 11, 703-712, 2008
1157. I. Tsuda, Number Created by the Interaction Between Consciousness and Memory: A Mathematical Basis for Prefefference, *Integrative Psychological and Behavioral Science*, 42, 153-156, 2008
1158. I. Tsuda, Y. Yamaguchi, S. Kuroda, Y. Fukushima and M. Tsukada, A Mathematical Model for the Hippocampus: Towards the Understanding of Episodic Memory and Imagination, *Prog. Theor. Phys. Suppl.*, 173, 99-108, 2008
1159. I. Tsuda, Hypotheses on the functional roles of chaotic transitory dynamics, *Chaos - A Focus Issue on Chaos in immune and cognitive systems* (ed. T. Arecchi) (accepted), Dec. 23, 2008, in press
1160. K. Matsumoto, H. Diebner, I. Tsuda and Y. Hosoï, Application of chaos theory to engine systems, *Proc. of Small Engine Technology Conference, Society of Automotive Engineers*, 32-010016, 2008
1161. A. Ishiguro and M. Koyama and D. Owaki and J. Nishii, Increasing stability of passive dynamic bipedal walking by exploiting hyperextension of knee joints, *Proc. of 4th International Symposium on Adaptive Motion in Animals and Machines*, 164-165, 2008
1162. A. Fujii and H. Suenaga and Y. Hashizume and J. Nishii, Variability of leg swing trajectories and their optimality, *Proc. of 4th International Symposium on Adaptive Motion in Animals and Machines*, 173-174, 2008
1163. Y. Taniaki and J. Nishii, Optimality of reaching movements based on energetic cost under the influence of signal-dependent noise, *Neural Information Processing - Lecture Notes in Computer Science*, 4984, 1091-1099, 2008
1164. J. Nishii and Y. Taniaki, Evaluation of trajectory planning models for arm reaching movements based on energy cost, *Neural Computation*, in press, 2009
1165. A. Takamatsu, E. Takaba, G. Takizawa, Environment-dependent morphology in plasmodium of true slime mold *Physarum polycephalum* and a network growth model, *Journal of Theoretical Biology*, 256, 29-44, 2009
1166. A. Takamatsu, Environment-dependent morphology in plasmodium of the true slime mold *Physarum polycephalum*, *Gordon research conference on theoretical biology & biomathematics* 2008, 2008
1167. M. Ito, A. Takamatsu, K. Yokotani, Analysis on transportation network in plasmodium of true slime mold, 6th Asian Biophysics Association Symposium, 114-115, 2009
1168. Masahiro Sekimoto, Soguru Arimoto, Sadao Kawamura, Ji-Hun Bae, Skilled-Motion Plannings of Multi-Body Systems Based upon Riemannian Distance, *Proc. of the 2008 IEEE International Conference on Robotics & Automation*, Pasadena, CA, USA, May 19-23, 2008, 1233-1238, 2008
1169. Mitsunori Uenuma, Guangqiang Lu, Sadao Kawamura, Shigen Ma, Passive Periodic Motions of Multi-Joint Robots by Stiffness Adaptation and DFC for Energy Saving, *Proc. of SICE Annual Conference 2008, The University Electro-Communications*, Japan, August 20-22, 2008, 2853-2858, 2008

## 2009

1170. Manabu Gouko, Koji Ito, An Action Generation Model by Using Time Series Prediction and Its Application to Robot Navigation, *International Journal of Neural Systems*, 19, 2, 105-113, 2009
1171. M. Takahashi, K. Takeeda, R. Osu, Y. Otsuka, T. Harawaka, M. Gouko and K. Ito, Electroencephalogram (EEG) Measurement During Ankle Motion, *Proceedings of the 3rd International Symposium on Mobiligence*, 149-152, 2009
1172. Naoki Tomi, Manabu Gouko, Koji Ito, Combined mechanisms of internal model control and impedance control under dynamical environments, *Proceedings of the 3rd International Symposium on Mobiligence*, 137-142, 2009
1173. M.N. Anwar, N. Tomi and K. Ito, Motor Imagery in Force Field Adaptation, *Proceedings of the 3rd International*

- Symposium on Mobiligence, 133-136, 2009
1174. T. Sakurada, H. Gomi, and K. Ito, Neural crosslinks construct the muscular and spatial coordination during bilateral gait movements, Proceedings of the 3rd International Symposium on Mobiligence, 125-128, 2009
1175. Marabu Gouko, Koji Ito, Environmental modeling and identification for autonomous mobile robot, Proceedings of the 3rd International Symposium on Mobiligence, 119-124, 2009
1176. Marabu Gouko, Koji Ito, Environmental identification based on changes in sensory information, Proceedings of the 14th International Conference on Advanced Robotics (ICAR2009), 1-7, 2009
1177. Naoki Tomi, Marabu Gouko, Koji Ito, Cooperative mechanisms of internal model control and impedance control under force fields, Proceedings of 19th International Conference on Artificial Neural Networks (ICANN2009), 628-637, 2009
1178. Mitsuru Takahashi, Marabu Gouko, Koji Ito, Fundamental Research about Brain Computer Interface for stroke rehabilitation, Italy-Japan International Seminar, Musculoskeletal System and Computational Neuro Science for Rehabilitation, 2009
1179. Mitsuru Takahashi, Marabu Gouko, Koji Ito, Fundamental Research about Electroencephalogram (EEG) - Functional Electrical Stimulation (FES) Rehabilitation System, Proceedings of the 2009 IEEE 11th International Conference on Rehabilitation Robotics (ICORR2009), 316-321, 2009
1180. Mitsuru Takahashi, Marabu Gouko, Koji Ito, Functional Electrical Stimulation (FES) Effects for Event Related Desynchronization (ERD) on Foot Motor Area, Proceedings of 2009 IEEE/ICME International Conference on Complex Medical Engineering (CME2009), 1-6, 2009
1181. Mitsuru Takahashi, Marabu Gouko, Koji Ito, Muscular Sensation Induce Event Related Desynchronization (ERd) on Foot Motor Area, Proceedings of 2009 IMEKO World Congress, 81-85, 2009
1182. Takayuki Nozawa, Toshiyuki Kondo, Construction of Reversible Lattice Molecular Automata, International Journal of Modern Physics C, 20, 6, 901-929, 2009
1183. Takayuki Nozawa, Toshiyuki Kondo, A comparison of artifact reduction methods for real-time analysis of fNIRS data, Lecture Notes in Computer Science 5618, 413-422, 2009
1184. Seimei Abe, Takayuki Nozawa, Toshiyuki Kondo, A Proposal of EMG-based Training Support System for Basketball Drilling, Lecture Notes in Computer Science 5617, 459-465, 2009
1185. Takayuki Nozawa, Toshiyuki Kondo, Effectiveness of Intrinsically Motivated Adaptive Agent for Sustainable Human-Agent Interaction, Lecture Notes in Computer Science 5864, 179-188, 2009
1186. Kawamori A, Matsushima T, Subjective value of risky foods for individual domestic chicks: a hierarchical Bayesian model, Animal Cognition (DOI:10.1007/s10071-009-0293-1, online), 2009
1187. Amata H, Kawamori A, Matsushima T, Social influences of competition on impulsive choices in domestic chicks, Biology Letters (DOI:10.1098/rsbl.2009.0748, on line), 2009
1188. Kawamori A, Matsushima T, Bayesian analysis for quantitative estimation of subjective values: a study of risk-sensitivity in domestic chicks, the 31st International Ethology Conference, August 19-24, 2009, University of Rennes, Rennes, France, 2009
1189. Matsushima T, Matsunami S and Amata H, Decision to leave a food patch of diminishing return: distinct neuro-cognitive processes from inter-temporal choice, the 31st International Ethology Conference, August 19-24, 2009, University of Rennes, Rennes, France, 2009
1190. Sercan Tahra Ali, Hiroyuki Kambara, Yasuharu Koike, A Comparison of Dimensionality Reduction Techniques for the P300 Response, i-CREATE'2009, 2009
1191. Charles S.D.Salka, Hiroyuki Kambara, Makoto Sato, Yasuharu Koike, Spatial Filtering and Single-Trial Classification of EEG during Vowel Speech Imagery, i-CREATE'2009, 2009
1192. Sercan Tahra Ali, Hiroyuki Kambara, Yasuharu Koike, Dimension Reduction Techniques for the P300 Response, 2009 IEEE 11th International Conference on Rehabilitation Robotics, 2009
1193. YKOIKE, K.YONEYAMA, KOHISHI, TKAWASE, HKAMBARA, Recalibration of time to contact, NEUROSCIENCE 2009, 209
1194. HKAMBARA, KKURASHIGE, DSHIN, YKOIKE, Role of efferent signal in weight perception without somatosensory feedback, NEUROSCIENCE 2009, 2009
1195. YKoike, K.Yoneyama, HKambara, Recalibration of time to contact, The 3rd International Symposium on Mobiligence, 2009
1196. Yan Li, Yasuharu Koike, Masashi Sugiyama, A Framework of Adaptive Brain Computer Interfaces, CISP'09-BMEF'09, 2009
1197. Ogawa T, Komatsu H, Condition-dependent and condition-independent target selection in macaque posterior parietal cortex, Journal of Neurophysiology, 101, 721-736, 2009
1198. Harada T, Goda N, Ogawa T, Ito M, Toyoda H, Sadato N, Komatsu H, Distribution of colour-selective activity in the monkey inferior temporal cortex revealed by functional magnetic resonance imaging, European Journal of Neuroscience, 30, 1960-1970, 2009
1199. Shinomoto S, Kim H, Shimokawa T, Matsuno N, Funahashi S, Shima K, Fujita I, Tamura H, Doi T, Kawano K, Inaba N, Fukushima K, Kurkin S, Kurata K, Taira M, Tsutsui K, Komatsu H, Ogawa T, Koike K, Tanji J, Toyama K, Relating neuronal firing patterns to functional differentiation of cerebral cortex, PLoS Comput Biol, 5, e1000433, 2009
1200. Hayashi, Y, Tamura Y, Sugawara K, Sawada Y, Roll of the rhythmic component in the proactive control of a human hand, Artif Life Robotics, 14, (2009), 14, 2009
1201. Hayashi, Y, Tamura Y, Sugawara K, Sawada Y, Why the hand motion proceeds the target in tracking experiment?, Proceedings of the 3rd International Symposium on Mobiligence, 2009
1202. Hiroaki Ishida, Kazumi Nakajima, Masahiko Inase, Akira Murata, Shared mapping of own and others' bodies in visuo-tactile bimodal area of the monkey parietal cortex, Journal of Cognitive Neuroscience, 22, 1, 83-96, 2010
1203. Akira Murata, Win Nyi Shein and Hideo Sakata, Object-centered position coding for hand manipulation activity in the parietal cortex of the monkey, 3rd International Symposium on Mobiligence on Awaji November, 2009
1204. Murata, A, Ishida, H, Nakajima, K, and Inase, M, Other's body representation referred to self body in the parietal cortex of the monkey, NIPS International Workshop for Scientific Study of Consciousness 2009 September Okazaki, 2009
1205. Murata, A, Ishida, H, Nakajima, K, and Inase, M, Other's body representation referred to self body in the parietal cortex of the monkey, IUPS 2009 July Kyoto, 2009
1206. Keisuke Okuno and Tetsunari Inamura, Estimation of other's sensor patterns based on motion imitation and communication, 10th International Symposium on Artificial Life and Robotics, 2010
1207. Tetsunari Inamura and Keisuke Okuno, Estimation of other's sensory patterns based on dialogue and shared motion experiences, 9th IEEE/RAS International Conference on Humanoid Robots, 617-623, 2009
1208. Keisuke Okuno and Tetsunari Inamura, Inference of other's sensorimotor patterns based on symbolic query with motion performance, The 3rd International Symposium on Mobiligence, 42-45, 2009
1209. J. Namikawa, J. Tani, Learning to imitate stochastic time series in a compositional way by chaos, Neural Networks, in press
1210. J. Tani, Autonomy of Self at criticality: The perspective from synthetic neuro-robotics, Adaptive Behavior, 17, 5, 421-443, 2009
1211. R. Nishimoto, J. Tani, Development of hierarchical structures for actions and motor imagery: a constructivist view from synthetic neuro-robotics study, Psychological Research, 73, 545-558, 2009
1212. H. Arie, T. Endo, T. Arakaki, S. Sugano, J. Tani, Creating novel goal-directed actions at criticality: a neuro-robotic experiment, New Mathematics and Natural Computation, 5, 1, 307-334, 2009
1213. M. Maniakkas, J. Tani, Acquiring rules for rules: neuro-dynamical systems account for meta-cognition, Adaptive Behavior, 17, 1, 58-80, 2009
1214. I. Igarí, J. Tani, Incremental Learning of Sequence Patterns with a Modular Network Model, Neurocomputing, 72, 1910-1919, 2009
1215. Matsuyama K, Takakusaki K, Organizing Principles of Projections of the Long Descending Reticulospinal Pathways and Their Targets: Spinal Commissural Neurons With Special Reference to the Locomotor Function, Handbook on White Matter: Structure, Function and Changes (Editors: Westland TB, Calton RN), 335-356, 2009
1216. Kumei S, Motomura W, Yoshizaki T, Takakusaki K, Okumura T, Troglitazone increases expression of E-cadherin and claudin-4 in human pancreatic cancer cells, Biochem. Biophys. Res. Comm, 382, 615-619, 2009
1217. Adachi M, Nonaka S, Katada A, Arakawa T, Ota R, Harada H, Takakusaki K, Hanbuchi Y, Laryngeal muscle activity and airway reflexes during a carbachol-induced REM sleep in decerebrate cats, Neuroscience Research, in press
1218. Takakusaki K, Okumura T, Koyama Y, Subcortical mechanisms of controlling muscle tone and locomotion with respect to the pathogenesis: Cataplexy in Narcolepsy, In: Narcolepsy: Symptoms, Causes and Diagnosis and Treatment. Nova Science Publishing Co, New York, USA, in press
1219. Takakusaki K, Iwamura H, Firing properties of the pedunculopontine tegmental nucleus neurons with respect to the basal ganglia modulation, Neuroscience Research, 65, Suppl. S71, 2009
1220. Tsuchiya Y, Takahashi N, Yoshizaki T, Tanno S, Ohira M, Motomura W, Tanno S, Takakusaki K, Kohgo Y, Okumura T, A Jak2 inhibitor, AG490, reverses lipin-1 suppression by TNF-alpha in 3T3-L1 adipocytes, Biochem. Biophys. Res. Comm, 360, 614-619, 2009
1221. Tanno S, Ohira M, Tsuchiya Y, Takeuchi T, Tanno S, Okumura T, Laryngeal muscle activity and airway reflexes during a carbachol-induced REM sleep in decerebrate cats, Internal Medicine, 48, 1263-1266, 2009
1222. Onuma Boonyarom, Naoki Kozuka, Kiyoji Matsuyama, Shinji Murakami, Effect of Electrical Stimulation to Prevent Muscle Atrophy on Morphological and Histological Properties of Hindlimb Suspended Rat Hindlimb Muscles, American Journal of Physical Medicine & Rehabilitation, 88, 9, 719-726, 2009
1223. T. Hosodo, F. Mori, et al, Characteristics of H- and M-waves recorded from rat forelimbs, Neuroscience Letters, 450, 239-241, 2009
1224. Y. Wada, F. Mori, et al, Distribution of dendrites from longissimus lumborum motoneurons stained intracellularly with biocytin in the adult cats, Journal of Veterinary Medical Science, in press
1225. Takakusaki K, Neural substrates for gait control in relation to the basal ganglia function, The Basal Ganglia in Health & Disease, Satellite Symposium for Neuro2009, 2009, 9.14-15, Okazaki, Japan
1226. Takakusaki K, The pedunculopontine tegmental nucleus (PPN) "from their rhythmic firing property to their roles for biological function, The 6th Congress of Asia Sleep Research Society (ASRS), Symposium on "Significance of various biological Rhythms", 2009, 10, 25-27, Osaka, Japan
1227. Takakusaki K, Basal Ganglia influences on brainstem locomotor and posture regions, Workshop on "Freezing of Gait (FoG)", 2010, 2, 25-26, Washington DC, USA
1228. Kiyoji Matsuyama, Masanori Ishiguro, Suguru Kobayashi, Mamoru Aoki, Spinal Neural Mechanisms in The Generation of Coordinated Quadrupedal Locomotion in Rabbits, Journal of Physiological Sciences (Proceedings of 36th International Congress of Physiological Sciences) (IUPS2009, Kyoto), 59, Suppl, 448, 2009
1229. Yutaka Fujito, Suguru Kobayashi, Kiyoji Matsuyama, Mamoru Aoki, Respiratory Rhythm Generation and its Raphe Modulation in *in vitro* Medullary Half-Slice Preparations of Neonatal Mice, Journal of Physiological Sciences (Proceedings of 36th International Congress of Physiological Sciences) (IUPS2009, Kyoto), 59, Suppl, 466, 2009
1230. Kiyoji Matsuyama, Masanori Ishiguro, Kaoru Takakusaki, Descending Routes of Locomotor Driving Signals Involved in The Generation of Coordinated Hopping Locomotion in Decerebrate Rabbits, Proceedings of The 3rd International Symposium on Mobiligence, 255-258, 2009
1231. Genko Oyama, Kenji Yoshimi, Shihoko Natori, Yoko Chikako, Yong-Ri Ren, Yasushi Shimo, Ryosuke Takahashi, Taizo Nakazato, Shigeru Kitazawa, and Nobutaka Hattori, Aging effect on dopamine release in parkin knockout mice, The Movement Disorder Society's 13th International Congress of Parkinson's Disease and Movement Disorders (MDS), 2009
1232. G Oyama, H Shiotsuki, K Yoshimi, S Natori, Y Chikako, YR Ren, K Ikeda, Y Shimo, R Takahashi, N Hattori, S Kitazawa, Reduced dopamine release in parkin knockout mice, XXXVII International Union of Physiological Sciences (IUPS), July 27-Aug 1, Kyoto, 2009
1233. S Natori, K Yoshimi, Y Shimo, N Hattori, S Kitazawa, Detecting reward-associated dopamine release in the striatum of behaving mice, XXXVII International Union of Physiological Sciences (IUPS), July 27-Aug 1, Kyoto, 2009
1234. \*K. YOSHIMI, Y. NAYA2, N. MITANI2, M. INOUE1, S. NATORI1, T. OCHIAI1, A. SUZUKI2, Y. EINAGA2, S. KITAZAWA1, Diamond microelectrode amperometry in the awake primate brain, 39th Annual Meeting, Society for Neuroscience, Chicago, U.S.A., Oct. 17-21, 2009
1235. \*AZ Weitemier, K. YOSHIMI2, Y. NAYA3, N. MITANI3, A. SUZUKI3, S. NATORI2, Y. EINAGA3, J. McHugh1, S. KITAZAWA2, Differential detection of monoamines and pH using diamond microelectrode, 39th Annual Meeting, Society for Neuroscience, Chicago, U.S.A., Oct. 17-21, 2009
1236. K. YOSHIMI1, Y. EINAGA2, T. NAKAZATO1, S. KITAZAWA1, Reward-related dopamine release in the rodent and primate brain, The 3rd International Symposium on Mobiligence, 2009
1237. Akira Murata, Hiroaki Ishida, Kazumi Nakajima, Masahiko Inase, Other's Body Representation Referred to Self Body in the Parietal Cortex of the Monkey, The Journal of Physiological Sciences, 59, Suppl. 1, 194, 2009
1238. Kazumi Nakajima, Futoshi Mori, Akira Murata, Masahiko Inase, Neuronal Activity in Primary Motor Cortex of a Japanese Monkey during Quadrupedal vs. Bipedal Locomotion on the Treadmill, The Journal of Physiological Sciences, 59, Suppl. 1, 449, 2009
1239. Atsushi Chiba, Ken-ichi Oshio, Masahiko Inase, Physiological Effects of the Upright Sitting on the Knees, The Journal of Physiological Sciences, 59, Suppl. 1, 483, 2009
1240. F. Mori and K. Nakajima, Adaptive and anticipatory locomotor control in bipedal walking monkeys, 2009 IEEE International Conference on Robotics and Automation, Kobe, Japan, 2009
1241. F. Mori and K. Nakajima, Cortical contribution to the interlimb and interlimb coordination during bipedal locomotion in monkeys, 19th International Society for Posture and Gait Research, Bologna, Italy, 2009
1242. Takeuchi, E, Yangghara, D, Ishida, A, and Yuzaki, M, Effects of Chb1 infusion on the hindlimb kinematics during treadmill locomotion in adult chb1-null mice, The 3rd International Symposium on Mobiligence, 161-164, 2009
1243. Kotajima, H, Yangghara, D, Narumi, S, and Yuzaki, M, Role of the Purkinje cell-specific G2 glutamate receptor in fear conditioned heart rate responses in mice, The 3rd International Symposium on Mobiligence, 220-223, 2009
1244. Yoshimasa Koyama Kazumi Takahashi, Yuka Abe, Ayo Sakuma, Yukihiko Kayama, Hypothalamic regulation of muscular tonus through the orenergic and non-orenergic systems, Proceedings of the 36th International Congress of Physiological Sciences, 449, 2009
1245. Natsuko Tsujino, Tomomi Tsunematsu, Yoshimasa Koyama, Akhiro Yamanka, Takashi Sakurai, Alterations in monoaminergic neurons in orexin neuron-ablated mice, Proceedings of the 36th International Congress of Physiological Sciences, 520, 2009
1246. Kazumi Takahashi, Tohru Kodama, Yoshiko Honda, Yoshimasa Koyama, Orexin facilitates GABA release from the substantia nigra pars reticulata and the pedunculopontine tegmental nucleus that regulate muscular tonus, The 39th Annual Meeting of Society for Neuroscience, 2009
1247. Keiko Ogawa, Kazumi Takahashi, Kunio Kitahama, Katsuo Yamazaki, Yoshimasa Koyama, Effects of the superior colliculus lesions upon rapid eye movements during paradoxical sleep in the rat, The 39th Annual Meeting of Society for Neuroscience, 2009
1248. Keiko Ogawa, Kazumi Takahashi, Kunio Kitahama, Katsuo Yamazaki, Yoshimasa Koyama, Inhibition of burst eye movements during paradoxical sleep after superior colliculus lesion, The 6th Congress of Asian Sleep Research Society, Program & Abstract, 215, 2009
1249. Yoshimasa Koyama, Kazumi Takahashi, Yoshiko Honda, Tohru Kodama, GABA release from the substantia nigra pars reticulata and the pedunculopontine tegmental nucleus is facilitated by orexin, The 6th Congress of Asian Sleep Research Society, Program & Abstract, 216, 2009
1250. Yoshimasa Koyama, Kazumi Takahashi, Yuka Abe, Ayo Sakuma, Kaoru Takakusaki, Tonic and phasic regulations of muscular tonus through the hypothalamus, Proceedings of the 3rd International Symposium on Mobiligence p.157-160, 157-160, 2009
1251. Oghihara, N., Hiraseki, E., Nakatsukasa, M., Experimental and computational studies of bipedal locomotion in the bipedally-trained Japanese macaque, D'Arout, K. and Vereecke, E.E. (eds) Studying Primate Locomotion: Linking Field and Laboratory Research, New York, Springer, in press
1252. Oghihara, N., Makishima, H., Aoi, S., Sugimoto, Y., Tsuchiya, K., Nakatsukasa, M., Development of an Anatomically Based Whole-Body Musculoskeletal Model of the Japanese Macaque (*Macaca fuscata*), American Journal of Physical Anthropology, 139, 323-338, 2009
1253. Oghihara, N., Makishima, H., Nakatsukasa, M., Three-dimensional musculoskeletal kinematics during bipedal locomotion in the Japanese macaque reconstructed based on an anatomical model-matching method, Journal of Human Evolution, in press
1254. Matsuura, Y., Oghihara, N., Nakatsukasa, M., A method for quantifying articular surface morphology of metacarpals using quadratic surface approximation, International Journal of Primatology, in press
1255. Oishi, M., Oghihara, N., Endo, H., Ichihara, N., Asari, M., Dimensions of forelimb muscles in orangutans and chimpanzees, Journal of Anatomy, 215, 373-382, 2009
1256. Oishi, M., Oghihara, N., Endo, H., Komiya, T., Kawada, S., Tomiyama, T., Sugura, Y., Ichihara, N., Asari, M., Dimensions of the foot muscles in the lowland gorilla, Journal of Veterinary Medical Science, 71, 821-824, 2009
1257. Kagaya, M., Oghihara, N., Nakatsukasa, M., Rib orientation and implications for orthograde positional behavior in non-human anthropoids, Primates, 50, 305-310, 2009
1258. Yasuhiro Sugimoto, Shinya Aoi, Naomichi Oghihara, Kazuo Tsuchiya, The Stabilizing function of musculoskeletal system for periodic motion, Advanced Robotics, 23, 5, 521-534, 2009
1259. Kazuhiko Nakatani, Yasuhiro Sugimoto, Koichi Osaka, Demonstration and Analysis of Quadrupedal Dynamic Walking, Advanced Robotics, 23, 5, 483-501, 2009
1260. Shinya Aoi, Naomichi Oghihara, Tetsuro Funato, Yasuhiro Sugimoto, Kazuo Tsuchiya, Evaluating functional roles of phase resetting in generation of adaptive human bipedal walking with a physiologically-based model of the spinal pattern

- generator, *Biological Cybernetics*, in press
1261. N. Oghara, S. Aoi, Y. Sugimoto, T. Funato, H. Makishima, M. Nakatsukasa and K. Tsuchiya, System biomechanics of bipedal walking in the Japanese macaque: Exploration of principal mechanism for adaptive locomotion, 3rd International Symposium on Mobiligence, Awaji, Japan, 2009
1262. N. Oghara, S. Aoi, Y. Sugimoto, K. Tsuchiya, and M. Nakatsukasa, Computer simulation study of bipedal walking in the Japanese macaque based on a musculoskeletal model, 3rd International Symposium on Mobiligence, Awaji, Japan, 2009
1263. Oghara, N., Biomechanical analyses and simulation of bipedal locomotion in the Japanese macaque, Workshop: Adaptive motion in man, animals, and machines, Jena, Germany, 2009
1264. N. Oghara, S. Aoi, Y. Sugimoto, K. Tsuchiya, and M. Nakatsukasa, Simulation study of bipedal locomotion in the Japanese macaque: Towards understanding the mechanisms of adaptive control and the evolution of human bipedalism, The 32nd Annual Meeting of the Japan Neuroscience Society, Nagoya, Japan, 2009
1265. Y. Sugimoto, H. Yoshioka, S. Katsunezuka, K. Ouka, Motion Analysis of Multi-Legged Passive Dynamic Walking, The 19th Intelligent System Symposium (FAN2009), 2009
1266. K. Tsuchiya, S. Aoi, T. Funato, N. Oghara, System Models of Animal Locomotion, Cognition for Technical Systems Fall Workshop, 2009
1267. S. Aoi, N. Oghara, T. Funato, Y. Sugimoto, and K. Tsuchiya, Generation of Adaptive Human Bipedal Locomotion Based on a Neuromusculoskeletal Model, The 3rd International Symposium on Mobiligence, 250-254, 2009
1268. T. Funato, S. Aoi, and K. Tsuchiya, An Analysis of the Kinematic Indices of Human Walking, The 3rd International Symposium on Mobiligence, 224-229, 2009
1269. Koh Hosoda, Yuki Sakaguchi, Hiroshi Takayama, and Takashi Takuma, Pneumatic-driven jumping robot with anthropomorphic muscular skeleton structure, *Autonomous Robots*, 28, 2010
1270. K.Tsujita, T.Kobayashi, T.Iinoura and T.Masuda, Feasibility Study on Stability of Gait Patterns with Changeable Body Stiffness using Pneumatic Actuators in Quadrapod Robot, *Advanced Robotics*, 23, 503-520, 2009
1271. Rodrigo da Silva Guemay, Hiroshi Aonuma, Koh Hosoda, and Minoru Asada, Using Micro-robots as a Tool for Insect Behavior Studies, Proceedings of Workshop on Mobiligence(held in conjunction with IROS 2009), 39-44, 2009
1272. Koh Hosoda, Yuki Sakaguchi, and Hiroshi Takayama, Anthropomorphic Monopod Bouncing Equipped with Biarticular Muscles, The 3rd International Symposium on Mobiligence, 64-67, 2009
1273. T.Kobayashi, K.Tsujita and T.Masuda, Stability of Quadraped Locomotion under Changeable Body Stiffness, Proc. of the 3rd Int. Symp. on Mobiligence, Awaji, Japan, 230-233, 2009
1274. T.Kobayashi and K.Tsujita, Stability of Gait Patterns with Changeable Body Stiffness in Quadraped Locomotion, Proc. of Int. Conf. FAN 2009, Aizu Wakamatsu, Japan, 371-376, 2009
1275. M.Goan, T.Fukaya and K.Tsujita, The More Rehearsal, the More Noise in Timing Patterns, Proc. of 20th Int. Conf. on Noise and Fluctuations, Pisa, Italy, 559-562, 2009
1276. Takashi Takuma, Katsuyoshi Tsujita, Koh Hosoda, Hironori Asada, Yasuyuki Ikezawa, Shogo Fujitani, Tatsuya Masuda, Tunable Leg Compliance Mechanism for Dynamic Locomotion utilizing Pneumatic Actuators, 2009 IEEE International Conference on Robotics and Automation Workshop, CD-ROM, 2009
1277. Takashi Takuma, Katsuyoshi Tsujita, Koh Hosoda, Tatsuya Masuda, The dynamic locomotion of the bipedal robot based on human musculoskeletal design, The 19th Intelligent System Symposium FAN09, 448-453, 2009
1278. Takashi Takuma, Masahiro Ikeda, Tatsuya Masuda, Development of the Spine Structure for the Generation of the Locomotion, The 3rd International Symposium on Mobiligence, 170-173, 2009
1279. Kousuke Inoue, Toward Synthetic Understanding of Snake Locomotion, The 3rd International Symposium on Mobiligence, 2009
1280. Tatsuya NISHIBE, Kousuke INOUE, Adaptive Control of a Snake-like Robot Interact with Ground Surface, Proc. 5th International Student Conference at Ibaraki University, 51-52, 2009
1281. Shiori TAGUCHI, Kousuke INOUE, Development of Artificial Muscle Spindles and Tendon Organs for Artificial Muscles, Proc. 5th International Student Conference at Ibaraki University, 49-50, 2009
1282. Hiroshi Yokoi and Kojiro Matsushita, Self-regulatory Hardware: Evolutionary Design for Mechanical Passivity on a Pseudo Passive Dynamic Walker, Artificial Life Models in Hardware (Ed. Andrew Adamatzky and Maciej Komorosinski), Springer-Verlag, 87-102, 2009
1283. Takeshi Uejima, Kahori Kita, Toshiyuki Fujii, Ryu Kato, Masatoshi Takita, Hiroshi Yokoi, Motion Classification using Epidual Electrodes for Low-Invasive Brain-Machine Interface, 31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC2009), 6469-6472, 2009
1284. Kahori Kita, Takeshi Uejima, Toshiyuki Fujii, Masatoshi Takita, Hiroshi Yokoi, Estimation of rat locomotion process through multirecording of epidural potentials, XXXVI International Congress of Physiological Sciences, Kyoto Japan, 2009
1285. Takafumi Suzuki, Naoki Kotake, Takuya Kohama, Osamu Fukayama, Kunihiko Mabuchi, Study on brain adaptation using rat-machine fusion systems and multi functional neural electrodes, Proc. of the 3rd International Symposium on Mobiligence, 238-241, 238-241, 2009
1286. Naoki Kotake, Takafumi Suzuki, Osamu Fukayama, Shohei Takeuchi, Kunihiko Mabuchi, Preliminary development of polyene flexible sensor for glutamate detection, *Neuroscience*, 2009, 28, 2009
1287. Osamu Fukayama, Takafumi Suzuki, Kunihiko Mabuchi, Analyzing transition in correlation between neural signals and locomotion through vehicular BMI RatCar, *Neuroscience*, 2009, 161, 2009
1288. Choi, K., Hirose, H., Sakurai, Y., Iijima, T., Koike, Y., Prediction of arm trajectory from the neural activity of the primary motor cortex with modular connectionist architecture, *Neural Networks*, 22, 1214-1223, 2009
1289. Sakurai, Y., Takahashi, S., Nomura, M., Dynamic changes of firing frequency and synchrony of the rat hippocampal neurons caused by BMI, Proceeding of 3rd International Symposium on Mobiligence, 206-210, 2009
1290. Takahashi, S., Sakurai, Y., Information in small neuronal ensemble activity in the hippocampal CA1 during delayed non-matching to sample performance in rats, *BMC Neuroscience*, 10, 115:1-11, 2009
1291. Takahashi, S., Sakurai, Y., Sub-millisecond firing synchrony of closely neighboring pyramidal neurons in hippocampal CA1 of rats during delayed non-matching to sample task, *Frontiers in Neural Circuits*, 3, 9:1-18, 2009
1292. Takahashi, M., Lauwereyns, J., Sakurai, Y., Tsukada, M., A code for spatial alternation during fixation in rat hippocampal CA1 neurons, *Journal of Neurophysiology*, 102, 556-567, 2009
1293. Hirokawa, J., Sadakane, O., Sakata, S., Bosch, M., Sakurai, Y., Yamamori, T., A critical role of the superior colliculus in enhancing spatial accuracy but not reaction time by audiovisual integration, 38th Society for Neuroscience Annual Meeting, Chicago, October 2009, 2009
1294. Sakurai, Y., How can brain-computer interfaces reveal real dynamics of working brain?, 8th Biennial Meeting of the Society for Applied Research in Memory & Cognition (SARMAC VIII), Kyoto, (2009年7月), 2009
1295. Okada K and Kobayashi Y, Characterization of oculomotor and visual activities in the primate pedunclopontine tegmental nucleus during visually guided saccade tasks, *European Journal of Neuroscience*, 30, 2211-2223, 2009
1296. Okada K, Toyama K, Inoue Y, Ito T and Kobayashi Y, Different Pedunclopontine Tegmental Neurons Signal Predicted and Actual Task Rewards, *The Journal of Neuroscience*, 29, 4858-4870, 2009
1297. Ken-ichi Okada & Yasushi Kobayashi, Analyses of the time course of neuronal activity of the pedunclopontine tegmental nucleus in monkeys for reward conditioned saccade task, Society for Neuroscience Meeting, 583.17, 2006
1298. K. Nakao, R. Matsuzaki, A. Noritake, K. Okada, Y. Kobayashi and K. Nakamura, Positive and negative value coding in the primate dorsal raphe nucleus, Society for Neuroscience Meeting, 683.13, 2009
1299. Yasushi Kobayashi, Reward prediction error computation in the pedunclopontine tegmental nucleus neurons, The 3rd International Symposium on Mobiligence, 153-156, 2009
1300. Yasushi Kobayashi and Ken-ichi Okada, The pedunclopontine tegmental nucleus neurons rely predicted and actual reward information, The international symposium on Construction and Reconstruction of the brain, 55, 2009
1301. Seki, K., Perlmutter, S.I. & Fetz, E.E., Task-dependent modulation of primary afferent depolarization in cervical spinal cord of monkeys performing an instructed delay task, *J. Neurophysiol.* 102: 85-99, *Journal of Neurophysiology*, 102, 2012-2020, 2009
1302. Seki, K., Spinal Control of Voluntary Movement, University of Newcastle, Motor Control Seminar, New Castle, UK, 2010
1303. Seki, K., A new role of spinal interneuronal networks for controlling volitional movement, 19th Society for the neural control of movement, 2009
1304. Seki, K., Function of spinal interneurons for controlling voluntary movements, Queen's university, Centre for Neuroscience studies, 2009 seminar series, 2009
1305. Tomohiko Takei, Kazuhiko Seki, Post-spike effects of spinal interneurons on hand muscles in monkeys performing a precision grip, The 39th annual meeting of the Society for the Neuroscience, 2009
1306. Nambu A, Basal ganglia: physiological circuits, *Squire LR (ed.) Encyclopedia of Neuroscience*, 2, 111-117, 2009
1307. Hatataka N, Tokuno H, Nambu A, Takada M, Transcranial doppler ultrasonography monitors cerebral blood flow changes in relation to motor tasks, *Cereb Cortex*, 19, 820-831, 2009
1308. Nambu A, Dynamic model of the basal ganglia functions and movement disorders, Nakanishi S, Kageyama R, Watababe D (eds) *Systems Biology: The Challenge of Complexity*, 91-97, 2009
1309. Nambu A, Hatanaka N, Takara S, Tachibana Y, Takada M, Information processing in the striatum of behaving monkeys, *The Basal Ganglia IX*, Eds Groenewegen HJ, Voom P, Berendse HW, Mulder AB, Cools AR, 41-48, 2009
1310. Iwamoto H, Tachibana Y, Sato N, Nambu A, Organization of motor cortical inputs to the subthalamic nucleus in the monkey, *The Basal Ganglia IX*, Eds Groenewegen HJ, Voom P, Berendse HW, Mulder AB, Cools AR, 109-117, 2009
1311. Takada M, Inoue K, Miyachi S, Okado H, Nambu A, Prevention of calyxin recruitment into nigral dopamine neurons from MPTP-induced degeneration in Maccaca fascicularis, *The Basal Ganglia IX*, Eds Groenewegen HJ, Voom P, Berendse HW, Mulder AB, Cools AR, 377-385, 2009
1312. J.H. Lee, Y. Kagamihara, S. Kakei, A new method for quantitative evaluation of neurological disorders based on EMG signals, *Recent Advances in Biomedical Engineering* Ed. By GR. Naik, 39-52, 2009
1313. Tsubomi H, Ikeda T, Hanakawa T, Hirose N, Fukuyama H, Osaka N, Parieto-occipital connectivity predicts top-down attentional effect in visual masking: an fMRI study with individual differences approach, *Neuroimage*, 45, 2, 587-597, 2009
1314. Toda H, Sawamoto N, Hanakawa T, Saito H, Matsumoto S, Okumura R, M, Ishikawa M, Fukuyama H, Hashimoto N, A novel composite targeting method using high-field magnetic resonance imaging for subthalamic nucleus deep brain stimulation, *Journal of Neurosurgery*, 111, 4, 737-45, 2009
1315. Tanaka S, Hanakawa T, Honda M, Watanabe K, Enhancement of pinch force in the lower leg by anodal transcranial direct current stimulation, *Experimental Brain Research*, 163, 3, 459-65, 2009
1316. Hanakawa T, Mirra T, Matsumoto R, Abe M, Inouchi M, Urayama S, Arami K, Honda M, Fukuyama H, Stimulus-response profile during single-pulse transcranial magnetic stimulation to the primary motor cortex, *Cerebral Cortex*, 19, 11, 2605-15, 2009
1317. Iseki K, Hanakawa T, Heshikawa K, Tomimoto H, Nankaku M, Yamuchi H, Hallett M, Fukuyama H, Gait disturbance associated with white matter changes: a gait analysis and blood flow study, *Neuroimage*, 49, 2, 1659-66, 2010
1318. Oshio R, Tanaka S, Sackto N, Sakabe M, Hanakawa T, Honda M, Differential effect of double-pulse TMS applied to dorsal premotor cortex and precrucis during internal operation of visuospatial information, *Neuroimage*, 49, 1, 1108-15, 2010
1319. Tanaka S, Honda M, Hanakawa T, Cohen LG, Differential contribution of the supplementary motor area to stabilization of a procedural motor skill acquired through different practice schedules, *Cerebral Cortex*, in press
1320. Aso K, Hanakawa T, Aso K, Fukuyama H, Cerebro-cerebellar interactions underlying temporal information processing, *Journal of Cognitive Neuroscience*, in press
1321. Iseki K, Ikeda A, Kihara T, Kawamoto Y, Mezaki T, Hanakawa T, Heshikawa K, Fukuyama H, Shibasaki H, Impairment of the cortical GABAergic inhibitory system in calcarine sulcus: a case report with neuroimaging, *Epileptic Disorder*, 11, 2, 126-31, 2009
1322. Hanakawa T, Hallett M, Mechanisms underlying cognitive and motor slowing in Parkinson's disease, 13th International Congress of Movement Disorder Society, Paris, France, 2009
1323. Hanakawa T, Keynote: Neuroimaging studies of motor-related behavior, Japan-Italy International Seminar: Musculoskeletal System and Computational Neuroscience for Rehabilitation, Genoa, Italy, 2009
1324. Omata K, Morimoto M, Hanakawa T, Honda M, Simultaneous recording of spontaneous EEG and fMRI, *Neuroscience* 2009, Chicago, USA, 2009
1325. Iseki K, Hanakawa T, Hallett M, Fukuyama H, Pathophysiology of gait disturbance in age-related white matter changes: a combined gait analysis and blood flow study, The 3rd International Congress on Gait and Mental Function, Washington DC, USA, 2010
1326. Hanakawa T, Kaneko E, Omata K, The neural correlates of the sensorimotor rhythms as revealed by simultaneous EEG-fMRI: implications for brain-computer interfaces, The 3rd International Symposium on Mobiligence 2009, Awaji, Japan, 2009
1327. H. Aonuma, M. Sakura, J. Ota, H. Asama, Social Adaptive Functions in Animals - Learning from Insect Social Behaviors, IROS 2009, 2009
1328. K. Kawabata, H. Aonuma, J. Ota, H. Asama, Modeling of Neuromodulation for Behavior Selection of the Cricket: Synthetic Neuroethology Approach, IROS 2009, 2009
1329. S. Yaho, Yikemoto, H. Aonuma and H. Asama, Development of Neurotransmitter Modulation on Aggression and Dominance Hierarchy in Cricket, *Gryllus Bimaculatus*, ICROS-SICE International Joint Conference 2009, 2009
1330. H. Aonuma, J. Ota, K. Kawabata, D. Kurabayashi, R. Kanazaki and H. Asama, Understanding social adaptive functions in animals, The 3rd international Symposium on Mobiligence, 3, 74-78, 2009
1331. K. Kawabata, T. Fujii, H. Aonuma, T. Suzuki, M. Ashikaga, J. Ota and H. Asama, A neuro-modulation model of behavior selection in the fighting behavior of male crickets, The 3rd international Symposium on Mobiligence, 3, 271-276, 2009
1332. S. Yano, Y. Ikemoto, H. Aonuma and H. Asama, Forgetting curve derived by serotonin hypothesis in cricket, *Gryllus bimaculatus*, The 3rd international Symposium on Mobiligence, 3, 324-327, 2009
1333. M. Sakura, M. Kikuchi and H. Aonuma, Role of nitric oxide and octopamine in the aggressive behavior of the cricket, The 3rd international Symposium on Mobiligence, 3, 328-331, 2009
1334. T. Mizuno, M. Sakura, M. Ashikaga, H. Aonuma, R. Chiba and J. Ota, Modeling of the effects of multi-modal inputs on the aggressive behavior using handicapped crickets, The 3rd international Symposium on Mobiligence, 3, 332-337, 2009
1335. H. Asama, H. Kurokawa, J. Ota, K. Sekiyama, Distributed Autonomous Robotic Systems 8 (Editor), Springer, 2009
1336. Norisuke Fujii, Reiko Inoue and Jun Ota, Rearrangement Task by Multiple Robots Using a Territorial Approach, Distributed Autonomous Robotic Systems 8, Eds. Hajime Asama, Haruhisa Kurokawa, Jun Ota and Kousuke Sekiyama, Springer, 325/333, 2009
1337. Masatoshi Ashikaga, Midori Sakura, Mika Kikuchi, Tetsutaro Hiraguchi, Ryosuke Chiba, Hiroshi Aonuma, Jun Ota, Establishment of Social Status without Individual Discrimination in the Cricket, *Advanced Robotics*, 23, 5, 563-578, 2009
1338. Jun Ota, Goal State Optimization Algorithm Considering Computational Resource Constraints and Uncertainty in Task Execution Time, *Robotics and Autonomous Systems*, 57, 4, 403-410, 2009
1339. Jun Ota, Rearrangement Planning of Multiple Movable Objects by a Mobile Robot, *Advanced Robotics*, 23, 1-2, 1/18, 2009
1340. Kousuke Inoue, Jun Ota, and Tamio Arai, Iterative Transportation by Multiple Mobile Robots Considering Unknown Obstacles, *Journal of Robotics and Mechatronics*, 21, 1, 44-56, 2009
1341. Masao Sugi, Ipppei Matsumura, Yusuke Tamura, Makoto Nikaido, Jun Ota, Tamio Arai, Kiyoshi Kotani, Kiyoshi Takamasa, Hiromasa Suzuki, Akio Yamamoto, Yoichi Sato, Seichi Shin, and Fumihiko Kamura, Quantitative Evaluation of Automatic Parts Delivery in "AttentiveWorkbench" Supporting Workers in Cell Production, *Journal of Robotics and Mechatronics*, 21, 1, 135-145, 2009
1342. Y. Ikemoto, Y. Ishikawa, T. Miura, H. Asama, A mathematical model for caste differentiation in termite colonies (Isoptera) by hormonal and pheromonal regulations, *Sociobiology*, 54, 3, 841-859, 2009
1343. Y. Ikemoto, S. Suzuki, H. Okamoto, H. Murakami, H. Asama, S. Morishita, T. Mishima, X. Lin, H. Itoh, Force Sensor System for Structural Health Monitoring Using Passive RFID Tags, *Sensor Review*, 29, 2, 127-136, 2009
1344. Kanako Nakajima, Soichiro Morishita, Tomoki Kazawa, Ryohi Kanazaki, Kuniki Kawabata, Hajime Asama, Taketoshi Mishima, Interpolation of binarized CLSM images for extraction of premotor neuron branch structures in silkworm moth, *Sensor Review*, 29, 2, 137-147, 2009
1345. Yewguan Soo, Masao Sugi, Masataka Nishino, Hiroshi Yokoi, Tamio Arai, Ryu Kato, Tatsuhisa Nakamura and Jun Ota, Quantitative Estimation of Muscle Fatigue using Surface Electromyography during Static Muscle Contraction, Proc. Int. Conf. IEEE Engineering in Medicine and Biology Society, 2975/2978, 2009
1346. Yewguan Soo, Masataka Nishino, Masao Sugi, Hiroshi Yokoi, Tamio Arai, Ryu Kato, Tatsuhisa Nakamura, and Jun Ota, Evaluation of Frequency Band Technique in Estimating Muscle Fatigue during Dynamic Contraction Task, Proceedings of the 2009 IEEE International Conference on Robotics and Automation, 1279/1284, 2009
1347. Yoshihiro Takebe, Norisuke Fujii, Reiko Inoue and Jun Ota, Realization of Rearrangement Task by Multiple Robots, Proc. ICROS-SICE International Joint Conference 2009, 2230/2234, 2009
1348. Masataka Nishino, Yuto Nakanishi, Masao Sugi, Yewguan Soo, Design of Gesture Interface for Deskwork Support System, Proc. ICROS-SICE International Joint Conference 2009, 2260/2267, 2009
1349. S. Yano, Y. Ikemoto, H. Aonuma, H. Asama, Development of Neurotransmitter Modulation on Aggression and Dominance Hierarchy in Cricket, *Gryllus Bimaculatus*, ICROS-SICE International Joint Conference 2009, 2254-2259, 2009
1350. Jun Ota, Hiroshi Aonuma and Hajime Asama, Mobiligence: Emergence of Adaptive Motor Function through Interaction among the Body, Brain and Environment, Workshops/Tutorials Proceedings of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, Workshop on Mobiligence: Social Adaptive Functions in Animals and Multi-Agent Systems, 39, 2009
1351. K. Kawabata, H. Aonuma, J. Ota, H. Asama, Modeling of Neuromodulation for Behavior Selection of the Cricket :

- Synthetic Neuroethology, Workshop on Mobilitance: Social Adaptive Functions in Animals and Multi-Agent Systems, International Conference on Intelligent Robots and Systems, 2009
1353. Hideo Sato, Kuniaki Kawahata, Tsubota Yugo, Hayato Kaetsu, Tsuyoshi Suzuki, Wireless camera nodes deployment by a teleoperated mobile robot for construction of sensor network, Proceedings of ICCAS-SICE 2009, pp3726-3730, 2009
1354. Y. Ikemoto, T. Miura, H. Asama, Adaptive Division of Labor Control for Robot Group, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2009), 2409-2414, 2009
1355. Q. An, H. Matsuoka, Y. Ikemoto, H. Asama, D. Chugo, K. Takakusaki, Extraction of Behavior Primitives in Human Standing-up Motion for Development of Power Assisting Machine, Proc. of the 2008 IEEE International Conference on Robotics and Biomimetics (ROBIO2008), 1995-2000, 2009
1356. Q. An, H. Matsuoka, Y. Ikemoto, H. Asama, Extraction of Behavior Primitives for Understanding Human Standing-up Motion, 2009 IEEE Int. Conf. on Mechatronics and Automation (ICMA '09), 1800-1805, 2009
1357. H. Matsuyama, H. Asama, M. Otake, Design of Differential Near-Infrared Spectroscopy Based Brain Machine Interface, 18th IEEE Int. Symp. on Robot and Human Interactive Communication (RO-MAN '09), 775-780, 2009
1358. M. Otake, M. Kato, T. Takagi, H. Asama, Development of Coimagination Method towards Cognitive Enhancement via Image Based Interactive Communication, 18th IEEE Int. Symp. on Robot and Human Interactive Communication (RO-MAN '09), 835-840, 2009
1359. Y. Ikemoto, Y. Ishikawa, T. Miura, H. Asama, A mathematical model for caste differentiation in termite colonies by hormonal and pheromonal regulations, Proc. of 3rd International Symposium on Mobilitance, 92-95, 2009
1360. M. Munayashi, Y. Ikemoto, M. Otake, T. Maeda, M. Kato, and H. Asama, Sense of Agency Elicited by Causal Relationship Between Motor Command and Sensory Feedback, Proc. of 3rd International Symposium on Mobilitance, 304-307, 2009
1361. S. Yano, Y. Ikemoto, H. Aonuma, H. Asama, Forgetting Curve Derived by Serotonin Hypothesis in Cricket, *Cryllus Bicruculatus*, Proc. of 3rd International Symposium on Mobilitance, 324-327, 2009
1362. Haupt SS, Sakurai T, Namiki S, Kazawa T, Kanzaki R, Olfactory information processing in moths, *The Neurobiology of Olfaction* (ed. Menzies A), CRC Press, Chapter 3, 2009
1363. Fukushima R and Kanzaki R, Modular subdivision of mushroom bodies by Kenyon cells in the silkworm, *J Comp Neurol*, 513, 315-330, 2009
1364. Fujiwara T, Kazawa T, Haupt S S, Kanzaki R, Ca<sup>2+</sup> imaging of identifiable neurons labeled by electroporation in insect brains, *NeuroReport*, 20, 12, 1061-1065, 2009
1365. Suzukawa J, Nakao M, Jimbo Y, Kanzaki R, and Takahashi H, Light-addressed stimulation under Ca<sup>2+</sup> imaging of cultured neurons, *IEEE Transactions on Biomedical Engineering*, 56, 11, 2660-2665, 2009
1366. Iwano M, Hill E, Mori A, Mishima T, Kumagai T, Ito K and Kanzaki R, Neurons Associated With the Flip-Flop Activity in the Lateral Accessory Lobe and Ventral Protocerebrum of the Silkworm Moth Brain, *J Comp Neurol*, 518, 366-388, 2010
1367. Nakajima K, Morishita S, Asama H, Kazawa T, Kanzaki R, Mishima T, Structural comparison of premotor neurons in silkworm moths, *FORMA* (in press), 2010
1368. Namiki S Haupt S S, Kazawa T, Takashima A, Ikeno H, and Kanzaki R, Reconstruction of virtual neural circuits in an insect brain, *Focus Review, Frontiers in Neuroscience*, 3, 2, 206-213, 2009
1369. Herianto, Daisuke Kurabayashi, Realization of an Artificial Pheromone System in Random Data Carriers using RFID Tags for Autonomous Navigation, *IEEE International Conference on Robotics and Automation*, 2288-2293, 2009
1370. Herianto, Daisuke Kurabayashi, Network Configuration in Artificial Pheromone System by Considering Exploration and Exploitation, *The 6th Int. Conf. on Ubiquitous Robots and Ambient Intelligence*, 534-538, 2009
1371. Daisuke Kurabayashi Ryohei Kanzaki, Understanding Adaptive Behavior Selection of a Micro Brain through Bio-Machine Hybrid System, 3rd Int. Symp. on Mobilitance, 79-82, 2009
1372. Takuro Moriyma, Daisuke Kurabayashi, Oscillator Network Model for Signal Buffer in Neural Circuits, 3rd Int. Symp. on Mobilitance, 343-347, 2009
1373. Ryo Minegishi, Atsushi Takashima, Daisuke Kurabayashi, Ryohei Kanzaki, Brain-Machine Hybrid System to Evaluate Adaptability in an Insect, 3rd Int. Symp. on Mobilitance, 299-303, 2009
1374. Atsushi Takashima, Ryo Minegishi, Daisuke Kurabayashi, Ryohei Kanzaki, Brain-Machine Hybrid System To Investigate Adaptability of an Insect Brain, 3rd Int. Symp. on Mobilitance, 338-342, 2009
1375. Atsushi Takashima, Ryo Minegishi, Daisuke Kurabayashi, Ryohei Kanzaki, Brain-Machine Hybrid System -To Investigate Adaptive Functionality of an Insect Brain- Full-day workshop in IROS2009, 2009
1376. Kanzaki R, Insect-Machine Hybrid System, *The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2009)* (St. Louis, Missouri, USA, from October 11 to 15) (Plenary Lecture) , 2009
1377. Kanzaki R, Odor source localization by an insect-robot hybrid system, *APACE2009* (Hawaii, USA, Oct 27-30) (Invited lecture) , 2009
1378. Kanzaki R, Pheromone source localization by an insect-robot hybrid system, *Meeting on Research in Taste & Smell* (Beijing, China Nov 15-17) (Invited lecture), 2009
1379. Kanzaki R, Insect-Machine Hybrid System, *Workshop on Robot-Animal Sensor Networks in Ecosystems, Organization: National Institute for Mathematical Sciences (NIMS) (Hotel Spapia, Daejeon, Republic of Korea, 3-4 December) (Keynote lecture)*, 2009
1380. Tabuchi M, Sakurai T, Mitsuno H, Minegishi R, Haupt SS, Shiotsuki T, Uchino K, Sezutsu H, Tamura T, Nakatani K, Kanzaki R, Milisecond Photoactivation of Bomblykol Receptor Neurons Expressing Channelrhodopsin-2 Triggers Pheromone Searching Behavior in Male Silkworms, *Chem Senses* (the Thirty-first Annual Meeting of the Association for Chemoreception Sciences (Hyatt Sarasota, Sarasota, Florida, April 23, 2009) (Travel Award), 34, 7, 50-51, 2009
1381. H. Imada, Y. Suehiro, T. Okuyama, D. Kurabayashi, A. Shimada, K. Naruse, H. Takeda, T. Kubo and H. Takeuchi, Analysis of Schooling-like Behavior of Medaka Fish and Identification of a Telencephalon-and-Hypothalamus-Preferential Gene in the Medaka Brain, 3rd Int. Symp. on Mobilitance, 295-298, 2009
1382. Y. Suehiro, T. Okuyama, H. Imada, K. Naruse, D. Kurabayashi, A. Shimada, H. Takeda, T. Kubo and H. Takeuchi, Optomotor Response of Medaka fish to Rotating Stripes at Sinusoidal Speed, 3rd Int. Symp. on Mobilitance, 308-311, 2009
1383. Hidetoshi Ikemoto, Tomoki Kazawa, Shigehiro Namiki, Stephan Stuechi-Haupt, Akira Takashima, Ryota Fukushima, Ikuko Nishikawa, Ryohei Kanzaki (Development of standard brain for silkworm moth, *Bombyx mori*, linked with a neuron database, *CNS2009* (July 18th ~ 23rd 2009, Berlin, Germany) , 2009
1384. Okada Y, Miyazaki S, Miyakawa H, Ishikawa A, Tsuji K, Miura T, Ovarian development and insulin-signaling pathways during reproductive differentiation in the queenless ponerine ant *Diacamma* sp., *J Insect Physiol*, in press, 2010
1385. Maekawa K, Ishitani K, Gotoh H, Comette R, Miura T, Juvenile hormone tier and vitellogenin gene expression related to ovarian development in primary reproductives, as compared to nymphs and nymphoid reproductives of the termite *Reticulitermes speratus*, *Physiol Entomol*, in press, 2010
1386. Ikemoto Y, Ishikawa Y, Miura T, Asama H, A mathematical model for caste differentiation in termite colonies (Isoptera) by hormonal and pheromonal regulations, *Sociobiol*, 54, 3, 841-859, 2009
1387. Shigenobu S, Bickel RD, Brisson JA, Butts T, Chang CC, Christiens O, Davis GK, Duncan EJ, Fenier DEK, Igo M, Jansen R, Lin GW, Lu HL, McGregor AP, Miura T, Smeaghe G, Smith JM, van der Zee M, Velarde R, Wilson MJ, Dearden PK, Stem DL, Comprehensive survey of developmental genes in the pea aphid, *Acyrtosiphon pisum*: frequent lineage-specific duplications and losses of developmental genes, *Insect Mol Biol*, in press
1388. Ishikawa A, Miura T, Differential regulations of wing and ovarian development and heterochronic changes of embryogenesis between morphs in wing polyphenism of the vetch aphid, *Evol Dev*, 11, 680-688, 2009
1389. Imai M, Narak Y, Tochima S, Miura T, Elaborate regulations of the predator-induced polyphenism in the water flea *Daphnia pulex*: kairomone-sensitive periods and life-history tradeoffs, *J Exp Zool*, 311A, 788-795, 2009
1390. Brisson JA, Ishikawa A, Miura T, Wing development genes of the pea aphid and differential gene expression between winged and unwinged morphs, *Insect Mol Biol*, in press, 2010
1391. Nakabachi A, Koshikawa S, Miura T, Miyagishima S, Genome size of *Pachypsilla venusta* (Hemiptera: Psyllidae) and the ploidy of its bacteriocyte, the symbiotic host cell that harbors intracellular mutualistic bacteria with the smallest cellular genome, *Bulletin of Entomological Research*, in press, 2010
1392. Toga K, Hojo M, Miura T, Maekawa K, Presoldier induction by juvenile hormone analogue in the nasute termite *Nasutitermes takasagoensis* (Isoptera: Termitidae), *Zoological Science*, 26, 382-388, 2009
1393. Kuroyanagi Y\*, Okuyama T\*, Suehiro Y, Imada H, Shimada A, Naruse K, Takeda H, Kubo T and Takeuchi H\* \*equal contribution †corresponding author, Proliferation zones in the adult medaka (*Oryzias latipes*) brain, *Brain Research*, in press, 2010
1394. Hon S\*, Kaneko K\*, Saito T, Takeuchi H and Kubo T\* \*equal contribution, Expression of two microRNAs, *ame-nir-276* and *-1000*, in the honeybee (*Apis mellifera*), *Apidologie*, in press, 2010
1395. Tadano H, Yamazaki Y, Takeuchi H†, Kubo T † \*Corresponding, Age- and division-of-labour-dependent differential expression of a novel non-coding RNA, *Nb-1*, in the brain of worker honeybees, *Apis mellifera* L., *Insect molecular biology*, 18, 715-767, 2009
1396. Fujiyuki T, Matsuzaka E, Nakaoka T, Takeuchi H, Wakamoto A, Ohka S, Sekimizu K, Nomoto A, Kubo T, Distribution of Kakugo virus and its effects on the gene expression profile in the brain of the worker honeybee *Apis mellifera* L., *Journal of Virology*, 83, 11560-11568, 2009
1397. Ueno T, Nakaoka T, Takeuchi H, Kubo T, Differential gene expression in the hypopharyngeal glands of worker honeybees (*Apis mellifera* L.) associated with an age-dependent role change, *Zoological science*, 26, 557-563, 2009
1398. H. Gotoh, R. Comette, S. Koshikawa, Y. Okada and T. Miura, Juvenile hormone determines the scaling relationship in stag beetle, *Evolution* 2009, 2009
1399. Toru Miura, Akiko Hattori, Shigeyuki Koshikawa, Satoshi Miyazaki, Hitoshi Miyakawa, Richard Comette, Insulin signaling pathway responsible for the soldier differentiation in a damp-wood termite *Hodoteropsis sjostedi*, *Evolution* 2009, 64, 2009
1400. H. Miyakawa, M. Imai, T. Miura, Screening and expression analysis of genes responding to predator kairomones in the water flea *Daphnia pulex*, *The Crustacean Society*, 100, 2009
1401. A. Ishikawa, Y. Okumura, Y. Nakagawa, T. Miura, Regulations of polyphenic wing development in the vetch aphid *Megoura viciae*: morphogenesis, tradeoffs, and gene expression, 8th International Symposium on Aphids Programme and Abstracts, 47, 2009
1402. Hideaki Takeuchi, Analysis of Social Interactions Using Adult Medaka Fish (Invited talk), *Common Themes and New Concepts in Sensory Formation*, The 18th CDB Meeting, 2009
1403. Haruka Imada, Yuji Suehiro, Teruhiro Okuyama, Daisuke Kurabayashi, Atsuko Shimada, Kiyoshi Naruse, Hiroyuki Takeda, Takeo Kubo, Hideaki Takeuchi, Analysis of Schooling-like Behavior of Medaka Fish and Identification of a Telencephalon-and-Hypothalamus-Preferential Gene in the Medaka Brain, *Proceeding of the Third International Symposium on Mobilitance*, 2009
1404. Yuji Suehiro, Teruhiro Okuyama, Haruka Imada, Atsuko Shimada, Kiyoshi Naruse, Hiroyuki Takeda, Takeo Kubo, Hideaki Takeuchi, Analysis of neural mechanism for the optomotor response of the medaka fish, *Common Themes and New Concepts in Sensory Formation*, The 18th CDB Meeting, 2009
1405. Yuji Suehiro, Teruhiro Okuyama, Haruka Imada, Atsuko Shimada, Kiyoshi Naruse, Hiroyuki Takeda, Takeo Kubo, Hideaki Takeuchi, Analysis of neural mechanism for the optomotor response of the medaka fish, *Society for Neuroscience 2009* (Chicago), 2009
1406. Teruhiro Okuyama, Yuji Suehiro, Haruka Imada, Atsuko Shimada, Kiyoshi Naruse, Hiroyuki Takeda, Takeo Kubo, Hideaki Takeuchi, Mapping of brain regions involved in female mating acceptance mediated by visual information in medaka fish, *Society for Neuroscience 2009* (Chicago), 2009
1407. Yoshikatsu Hayashi, Mai Yuki, Ken Sugawara, Tomonori Kikuchi and Kazuki Tsuji, Analysis and modeling of ants' behavior from single to multi-body, *Journal of Artificial Life and Robotics*, 120-123, 2008
1408. Kikuchi T, Mizuzaki S, Ohnishi S, Takahashi J, Nakajima Y, Tsuji K, Small queens and big headed workers in a monomorphic ponerine ant, *Naturwissenschaften*, 95, 10, 963-968, 2008
1409. Suwabe M, Ohnishi H, Kikuchi T, Tsuji K, Seasonal and daily activity patterns of tramp and endemic ants in the northern forest of Okinawa Island, *Ecological Research*, 24, 3, 637-643, 2009
1410. Kikuchi T, Nakagawa T, Tsuji K, Changes in relative importance of multiple social regulatory forces with colony size in the ant *Diacamma* sp. from Japan, *Animal Behaviour*, 76, 6, 2069-2077, 2008
1411. Dobata S, Sasaki T, Mori H, Hasegawa E, Shimada M, Tsuji K, Cheater genotypes in the parthenogenetic ant *Pristomyrmex punctatus*, *Proceedings of the Royal Society of London, Series B*, 276, 2, 567-574, 2009
1412. Ohtsuki H, Tsuji K, Adaptive reproduction schedule as a cause of worker policing in social Hymenoptera: a dynamic game analysis, *The American Naturalist*, 173, 6, 747-758, 2009
1413. Matsura K, Vargo E L, Kawatsu K, Labadie P-E, Nakano H, Yashiro T, Tsuji K, Queen succession through asexual reproduction in termites, *Science*, 323, 5922, 1687-1687, 2009
1414. Kikuchi T, Suwabe M, Tsuji K, Durability of the effect of gamergate presence information in *Diacamma* sp. from Japan, *Physiological Entomology*, in press
1415. Okada Y, Miyazaki S, Miyakawa H, Ishikawa A, Tsuji K, Miura T, Ovarian development and insulin-signaling pathways during reproductive differentiation in the queenless ponerine ant *Diacamma* sp., *Journal of Insect Physiology*, in press
1416. Tsuji K, What brings peace to the world of ants (Hymenoptera: Formicidae)?, *Mymecological News*, in press
1417. Mai Yuki, Yoshikatsu Hayashi, Ken Sugawara, Analysis and Modeling of *Diacamma* workers' Behavior, *Proc. of 14th Int. Symp. on Artificial Life and Robotics 2009*, 2008
1418. N. Fujiwara-Tsujii, K. Tokunaga, T. Akino, K. Tsuji, R. Yamaoka, Identification of the chemical bond between leader and follower ants during tandem running in *Diacamma* sp. from Japan (Hymenoptera: Formicidae), *The 3rd International Symposium on Mobilitance*, 312-315, 2009
1419. K. Sugawara, M. Yuki, Y. Hayashi, K. Yaegashi, T. Kikuchi, K. Tsuji, Analysis of ant's behavior from single to multibody, *The 3rd International Symposium on Mobilitance*, 320-323, 2009
1420. K. Tsuji, H. Ohtsuki, H. Shimoi, T. Kikuchi, H. Ohnishi, M. Yuki, K. Yaegashi, Y. Hayashi, K. Sugawara, R. Yamaoka, Colony-size dependent adaptive strategies in an ant society and their underlying self-organized regulation, *The 3rd International Symposium on Mobilitance*, 343-351, 2009
1421. Takafumi Takayama, Toshinobu Shimoi, Takuro Sakuramori, Akira Fujii, Kohji Hotta, Kotaro Oka, In Vivo pH Responses Evoked by Electrical and Sound Stimulation in Hippocampal Formation of Female zebra finch, *36th International Congress of Physiological Sciences*, P4AM-16-25, 2009
1422. M. Yamamoto, F. Takayama, A. Fujimoto, K. Hotta, and K. Oka, Direct evidence of neuronal projection between hippocampal formation and auditory area by fluorescent dye imaging, 3rd Mobilitance Symposium, 305, 2009
1423. F. Takayama, M. Yamamoto, H. Horia, K. Hotta, and K. Oka, pH responses in hippocampal formation of the zebra finch evoked by sound stimulation, 3rd Mobilitance Symposium, 306, 2009
1424. Masaki Ando, Masafumi Hagiwara, 3D Character Creation System Using Kansei Rule with the Fitness Extraction Method, *IEEE International Conference on Fuzzy Systems, FUZZ-IEEE 2009*, 1507-1512, 2009
1425. Ji-Soo Keum, Hyon-Soo Lee, Masafumi Hagiwara, A novel speech/music discrimination using feature dimensionality reduction, *International Symposium on Advanced Intelligent Systems (ISIS 2009)*, 129-132, 2009
1426. Ei-ichi Izawa, Shigeno Watanabe, Does allopreening of crows function as dominance signaling?, *International Ethological Conference 2009*, 278, 2009
1427. Mihoko Otake, Motochiro Kato, Toshihisa Takagi and Hajime Asamar, Coimagination Method: Communication Support System with Collected Images and Its Evaluation via Memory Task, "Universal Access in Human-Computer Interaction" LNCS 5614, ed by C. Stephanidis, Springer, 403-411, 2009
1428. Akira Uno, Taeko N. Wydell, Motochiro Kato, Kanae Itoh, Fumihiko Yoshino, Cognitive Neuropsychological and Regional Cerebral Blood Flow Study of a Japanese-English Bilingual Girl with Specific Language Impairment (SLI), *Cortex*, 45, 154-163, 2009
1429. Hidehiko Takahashi, Motochiro Kato, Masato Matsura, Dean Mobbs, Tetsuya Suhara, Yoshiro Okubo, When your gain is my pain and your pain is my gain: Neural correlates of envy and Schadenfreude, *Science*, 323, 937-939, 2009
1430. Shoko Nozaki, Motochiro Kato, Harumasa Takano, Hiroshi Ito, Hidehiko Takahashi, Ryoukai Anakawa, Masaki Okumura, Yota Fujimura, Ryohei Matsumoto, Miho Ota, Fumihiko Yasuno, Akihiko Takano, Akihiko Otsuka, Yoshiro Okubo, Haruo Kashima, and Tetsuya Suhara, Regional Dopamine Synthesis in Patients with Schizophrenia using L-[β-11C]DOPAPET, *Schizophrenia Research*, 108, 78-84, 2009
1431. Tatsuhiro Yagihashi, Motochiro Kato, Kosuke Izumi, Rika Kosaki, Kaori Yago, Kazuo Tsubota, Yuji Sato, Minoru Okubo, Goro Watanabe, Takao Takahashi, Kenjiro Kosaki, Case Report: Adult Phenotype of Multivill-Smith Syndrome, *American Journal of Medical Genetics Part A*, 149A, 496-500, 2009
1432. Hidehiko Takahashi, Takashi Ideno, Shigetaka Okubo, Hiroshi Matsui, Kazuhisa Takemura, Masato Matsura, Motochiro Kato, Yoshiro Okubo, Impact of changing the Japanese term for 'schizophrenia' for reasons of stereotypical beliefs of schizophrenia in Japanese youth, *Schizophrenia Research*, 112, 149-152, 2009
1433. Toshiyuki Kunihara, Motochiro Kato, Robert Reverser, I Gusti Rai Tirta, Suicide rate in Bali. (letter) , *Psychiatry and Clinical Neuroscience*, 63, 701, 2009
1434. Ryoukai Anakawa, Tetsuya Ichimya, Hiroshi Ito, Akihiko Takano, Masaki Okumura, Hidehiko Takahashi, Harumasa Takano, Fumihiko Yasuno, Motochiro Kato, Yoshiro Okubo, Tetsuya Suhara, Increase in thalamic binding of [11C]PE2I in patients with schizophrenia: a positron emission tomography study of dopamine transporter, *Journal of Psychiatric Research*, 43, 1219-1223, 2009
1435. Masaru Minura, Motochiro Kato, Haruo Kashima, Neuro-Behcet's disease presenting with amnesia and frontal dysfunction, *Clinical Neurology and Neurosurgery*, 111, 889-892, 2009
1436. Toshiyuki Kunihara, Motochiro Kato, Robert Reverser, I Gusti Rai Tirta, Risk factors for suicide in Bali: a psychological autopsy study, *BMC Public Health*, 9, 327, 2009

1437. Hidehiko Takahashi, Motoichiro Kato, Sassa Takeshi, Michihiko Koeda, Noriaki Yahara, Tetsuya Suhara, Yoshiro Okubo, Functional Deficits in the Extrastriate Body Area During Observation of Sports-Related Actions in Schizophrenia, *Schizophrenia Bulletin* (in press)
1438. Satoshi Umeda, Masaru Mimura, Motoichiro Kato, Acquired personality traits of autism following the damage to the medial prefrontal cortex, *Social Neuroscience* (in press)
1439. Masaru Mimura, Fumiko Hoeffl, Motoichiro Kato, Nobuhisa Kobayashi, Kristen Sheau, Debra Mills, Albert Gahburda, Julie Korenberg, Ursula Bellugi, Allan L. Reiss, Orbitofrontal activation and hypersociability in Williams Syndrome, *Journal of Neurodevelopmental Disorders* (in press)
1440. Daisuke Fujiwara, Sune Park, Rieko Kimura, Ikuko Suyama, Mari Takeuchi, Saori Hashiguchi, Joichiro Shirahase, Motoichiro Kato, Junzo Takeda, Haruo Kashima, Unmet Supportive Needs of Cancer Patients in an Acute-care Hospital in Japan - a census study, *Supportive Care in Cancer* (in press)
1441. Hidehiko Takahashi, Harumasa Takano, Tatsui Osaka, Fumitoshi Kodaka, Yoshiyuki Hirano, Ryosuke Arakawa, Hideyuki Kikyo, Yoshiro Okubo, Motoichiro Kato, Takayuki Obata, Hiroshi Ito, and Tetsuya Suhara, Contribution of dopamine D1 and D2 receptors to amygdala activity in human, *The Journal of Neuroscience* (in press)
1442. K. Sasaki, K. Yamasaki, K. Tsuchida, T. Nagao, Gonadotrophic effects of dopamine in isolated workers of the primitively eusocial wasp, *Polistes chinensis*, *Naturwissenschaften*, 96, 625-629, 2009
1443. K. Sasaki, T. Abe, Y. Yoshida, K. Asakawa, A homeotic mutation influences the wing vibration patterns during mating in males of the silkworm moth *Bombyx mori*, *Journal of Insect Physiology*, 55, 726-734, 2009
1444. Y. Nishi, K. Sasaki, T. Miyatake, Biogenic amines, caffeine and tonic immobility in *Tribolium castaneum*, *Journal of Insect Physiology*, 56, in press, 2010
1445. T. Nagao, A. Kishigami, K. Sasaki, Y. Tamori, Neurohormonal control of development and motivation of instinctive behavior in male crickets, 6th Asian Biophysics Association Symposium, 125-126, 2009
1446. K. Harano, K. Sasaki, T. Nagao, M. Sasaki, S. Tanaka, Role of brain dopamine in insect reproduction: comparison between honeybees and locusts, 16th International Congress of Comparative Endocrinology, 167, 2009
1447. A. Kishigami, Y. Watanabe, M. Hirata, T. Suzuki, and Y. Takahara, TRP channel of squid photoreceptor cells has affinity to Inositol-1,4,5-trisphosphate, Proceedings of the 3rd European Conference on Chemistry for Life Sciences (September 2-5, 2009, Frankfurt am Main, Germany), in press, 2009
1448. Y. Masuda, Y. Tamori, Magneto-encephalographic response to the second-ordered visual attributes, Perception supplement (32nd European Conference on Visual Perception), 38, 127, 2009
1449. Y. Tanaka, Y. Tamori, N. Asakura, R. Suzuki, Dynamic imagery can enhance contrast sensitivity improvement by imagery, Perception supplement (32nd European Conference on Visual Perception), 38, 177, 2009
1450. Ogawa, H., Directional-dependent plasticity in cercal-to-giant interneuron synapses in the cricket wind-sensitive system, Proceedings of the 3rd International Symposium on Mobilitance, 277-280, 2009
1451. R. Okada, H. Ikeno, T. Kimura, M. Ohashi, H. Aonuma, E. Ito, Markov model of honeybee social behavior, Information, in press, 2010
1452. M. Ohashi, R. Okada, T. Kimura, H. Ikeno, Observation system for the control of the hive environment by the honeybee (*Apis mellifera*), *Behav Res Methods*, 41, 782-786, 2009
1453. R. Okada, H. Ikeno, M. Ohashi, T. Kimura, E. Ito, Observations and computer simulation of the social behavior in the honeybee, The 3rd International Symposium on Mobilitance in Awaji, 87-91, 2009
1454. K. Iwata, M. Ohashi, T. Akamatsu, R. Okada, H. Ikeno, Carbon cycling of a honeybee colony under the environmental variation, The 3rd International Symposium on Mobilitance in Awaji, 316-319, 2009
1455. Jin DZ, Fujii N, Graybiel AM, Neural representation of time in cortico-basal ganglia circuits, Proceedings of the National Academy of Sciences USA, 106, 45, 19156-19161, 2009
1456. Z. C. CHAO, Y. NAGASAKA, N. FUJII, Long-term asynchronous decoding of multiple motor parameters using electrocorticographic signals in monkey 360.2/BB6, *Neuroscience* 2009, 2009
1457. K. TAKEKAWA, Y. NAGASAKA, Z. C. CHAO, Y. KUNIOYOSHI, N. FUJII, Granger causality revealed dynamic modulation of causal relationships in macaque frontal cortex 360.3/BB7, *Neuroscience* 2009, 2009
1458. K. SUZUKI, Z. C. CHAO, N. FUJII, Decoding abstract symbols by near-infrared spectroscopic signals 360.4/BB8, *Neuroscience* 2009, 2009
1459. T. YANAGAWA, Y. NAGASAKA, N. FUJII, Phase angle distribution of cortical synchronization reflects structural connectivity of cortical regions 360.11/BB15, *Neuroscience* 2009, 2009
1460. Makino Y, Yano M, Investigating the Underlying Intelligence Mechanisms of the Biological Olfactory System, *Advances in Artificial Intelligence*, in press, 2010
1461. Matsuzaka, Y., Sakamoto, K., Tanaka, T., Furusawa, Y., Mushiake, H., Cannula-aided penetration: A simple method to insert structurally weak electrodes into brain through the dura mater, *Neurosci. Res.* 65, 126-129, 2009
1462. Sakamoto K, Nakajima H, Suzuki T, Yano M, A "global closure", effect in contour Integration. Koeppe M. et al.(Eds) *ICNIP 2008, Part I LNCS 5506*, 258-265, 2009
1463. Sakamoto K, Matsuzaka Y, Suenaga T, Watanabe H, Kobayashi R, Fukushima T, Katayama N, Tanaka T, Koyanagi M, Mushiake H, A simple device allowing silicon microelectrode insertion for chronic neural recording in primates, The 4th International IEEE EMBS Conference on Neural Engineering, 104-107, 2009
1464. Kobayashi R, Kanno S, Lee S, Fukushima T, Sakamoto K, Matsuzaka Y, Katayama N, Mushiake H, Koyanagi M, Tanaka T, Development of double-sided Si neural probe with microfluidic channels using wafer direct bonding technique, The 4th International IEEE EMBS Conference on Neural Engineering, 96-99, 2009
1465. Masahiro Shimizu and Akio Ishiguro, An Amoeboid Modular Robot That Exhibits Real-time Adaptive Reconfiguration, The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, M011.4.3, pp.1496-1501, 2009
1466. Dai Owaki, Koichi Osaka and Akio Ishiguro, Understanding the Common Principle underlying Passive Dynamic Walking and Running, The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, Tu11.7.2, pp.3208-3213, 2009
1467. Masahiro Shimizu and Akio Ishiguro, A Collective Behavioral Approach to Understanding Mobilitance, The 3rd International Symposium on Mobilitance in Awaji, 102-107, 2009
1468. Dai Owaki, Koichi Osaka and Akio Ishiguro, Implicit Control Law That Enables Stable Passive Dynamic Running, The 3rd International Symposium on Mobilitance in Awaji, 352-356, 2009
1469. Uno, Ryoko, & T Ikegami, T. The role of uncertainty in communication: Analysis of atypical grammatical usage and simulating game players, Minett, James W. & Wang, William S-Y. (eds) *Language, Evolution, and the Brain*. Hong Kong: City University of Hong Kong Press, 2 3 9 - 2 6 0, 2009
1470. Ikegami, Takashi, *Rehabilitating Biology as a Natural History*, *Adaptive Behavior*, 17, 325-328, 2009
1471. Aucouturier, J.J. and Ikegami, T. The Illusion of Agency: Two Engineering Approaches to Compromise Autonomy and Reactivity in an Artificial System, *Adaptive Behavior*, 17, 402-420, 2009
1472. Suzuki, K., Ikegami, T. Shapes and Self-movements in Proto-Cell Systems, *Artificial Life*, 15, 1, 59-70, 2009
1473. Toyota, T., Maru, N., Hanczyc, M.M., Ikegami, T., Self-Propelled Oil Droplets Consuming "Fuel" Surfactant", *J. Amer. Chem. Soc.*, 131, 5 0 1 2 - 5 0 1 3, 2009
1474. Hanczyc, M and Ikegami, T., Protocells as smart agents for architectural design, *Technoethics Arts*, 7, 2, 1 1 7 - 1 2 0, 2009
1475. Ikegami, T. and Hanczyc, M.M., The search for a first cell under the maximalism design principle, *Technoethics Arts*, 7, 2, 153-164, 2009
1476. Naoto Horibe, Martin M. Hanczyc, Takashi Ikegami, Shape and Motion Dynamics in Self-Moving Oil Droplets, Proceedings of the 3rd Mobilitance conference, pp.367-371, 2009
1477. Sato, T, Iizuka, H and Ikegami, T, Simulating Active Perception and Body Images with a Computational Model, The 5th Asia-Pacific Computing and Philosophy Conference, 1 0 0 - 1 0 5, 2009
1478. Hubert, J, Matsuda, E., Silverman, E. and Ikegami, T, A Robotic Approach to Understanding Robustness, The 3rd Mobilitance conference, 361-366, 2009
1479. Ogaï, Y., Uno, R. and Ikegami, T., From Active Perception to Language, The 3rd Mobilitance conference, 382-386, 2009
1480. Eric Silverman and Takashi Ikegami, Defining Robustness in Artificial Life, The 9th Asia-Pacific Complex Systems Conference Complex09, 2009
1481. Ikegami, T. and Hanczyc, M.M., Is Life an Emergent property?, The Open Questions on The Origins of Life (organized by Kepa Ruiz Mirazo and Pier Luigi Luisi, San Sebastian), May, 2009
1482. Ikegami, T., Homeodynamics, Shape and Motion dynamics in Self-Moving Oil Droplets, What Is Evolution? (organized by Masatoshi Murase, Kyoto), Oct, 2009
1483. M. Iima and A. S. Mikhailov, Propulsion hydrodynamics of a butterfly micro-swimmer, *Europhysics Letters*, 85, 44001, 2009
1484. M. Iima and Y. Nishizawa, Unstable periodic solution controlling collision of localized convection cells in binary fluid mixture, *Physica D*, 238, 449-460, 2009
1485. Y. Tetsuka and M. Iima, Flow transitions in the surface switching of rotating fluid, *Journal of Fluid Mechanics*, 636, 475-484, 2009
1486. T. Shibuya, N. Hirai, Y. Sakamoto, and J. Komuro, Effects of morphological characteristics of *Cucumis sativus* Seedlings grown at different vapor pressures deficits on initial colonization of *Bemisia tabaci* (Hemiptera: Aleyrodidae), *Journal of Economic Entomology*, 102, 2265-2267, 2009
1487. K. Senda, T. Obata, M. Kitamura, T. Nishikata, On flight mechanics of flapping butterfly, *IEEE International Conference on Robotics and Automation*, 17-22, 2009
1488. K. Senda, M. Iima, and N. Hirai, Modeling and emergence of flapping flight of butterfly based on experimental measurements, *The 3rd International Symposium on Mobilitance*, 393-398, 2009
1489. M. Iima, An application of generalized Blasius formula to insect's flapping flight, *Proceedings of ISABMEC 2009*, 2009
1490. Huang, G H, T. Hirovartari, N. Hirai, M. Wang and M. Ishii, Phylogeny of Tineidae (Lepidoptera: Tineoidea) based on mitochondrial COI gene sequences, *The 6th Asia - Pacific Congress of Entomology (APCE 2009)*, 2009
1491. Sakamoto, Y., N. Hirai, M. Yago, and M. Ishii, Host - plant preference and Wolbachia infection in an endangered lycanid butterfly, *Zizina emelina*, of the Toyonaka population in Osaka Prefecture, central Japan, *The 6th Asia - Pacific Congress of Entomology (APCE 2009)*, 2009
1492. T. Aoki and T. Aoyagi, Co-evolution of phases and connection strengths in a network of phase oscillators, *Physical Review Letters*, 102, 3, 034101, 2009
1493. T. Tanaka, T. Kaneko, T. Aoyagi, Recurrent infomax generates cell assemblies, neuronal avalanches, and simple cell-like selectivity, *Neural Computation*, 21, 4, 1038-1067, 2009
1494. T. Aoki, K. Ota, K. Kurata, T. Aoyagi, Ordering Process of Self-Organizing Maps Improved by Asymmetric Neighborhood Function, *Cognitive Neurodynamics*, 3, 9-15, 2009
1495. K. Ota, M. Momura, T. Aoyagi, Weighted spike-triggered average of a fluctuating stimulus yielding the phase response curve, *Physical Review Letters*, 103, 2, 024101, 2009
1496. M. Nomura, D. Ito, H. Tamate, K. Gohara and T. Aoyagi, Estimation of functional connectivity that causes burst-like population activities, *FORMA*, 24, 1, 11-16, 2009
1497. T. Tanaka, T. Aoki, and T. Aoyagi, Dynamics in Co-evolving Networks of Active Elements, *FORMA*, 24, 1, 17-22, 2009
1498. J. Nishii, Y. Tanai, Evaluation of trajectory planning models for arm reaching movements based on energy cost, *Neural Computation*, 21, 9, 2634-2657, 2009
1499. J. Nishii, Constraint and exploitation of redundant degrees of freedom during walking, *Proc. of the 3rd International Symposium on Mobilitance 2009*, 417-420, 2009
1500. S. Kaichida, Y. Hashizume, J. Nishii, An analysis of leg trajectories of human walking from the view point of joint coordination, *Proc. of the 3rd International Symposium on Mobilitance 2009*, 409-412, 2009
1501. R. Fukuda, J. Nishii, The effect of freezing and freeing of degree of freedom on learning, *Proc. of the 3rd International Symposium on Mobilitance 2009*, 413-416, 2009
1502. J. Nishii, Y. Tanaka, H. Suenaga, Optimality of leg swing trajectories of forward and, *Abstract of Progress in Motor Control 2009*, A2-48, 2009
1503. S. Kaichida, Y. Hashizume, J. Nishii, An analysis of joint coordination during human, *Abstract of Progress in Motor Control 2009*, A1-43, 2009
1504. Y. Hashizume, J. Nishii, Intermediate selection pressure bring in the, *Proceedings of the 2nd Swarm Intelligence Algorithms*, 10-15, 2009
1505. Kagawa, Y., Takamatsu, A., Synchronization and spatiotemporal patterns in coupled phase oscillators on a weighted planar network, *Phys. Rev. E*, 79, 046216, 2009
1506. S. Watanabe, A. Tero, A. Takamatsu, T. Nakagaki, Rail grid optimization by an algorithm biologically inspired from an amoeba-like organism of true slime mold, *Proceedings of the 2009 International Symposium on Nonlinear Theory and its Applications*, Hokkaido, 356-359, 2009
1507. S. Watanabe, A. Tero, A. Takamatsu, T. Nakagaki, Rail grid optimization by an algorithm inspired from Physarum, *Proceedings of 3rd International Symposium on Mobilitance in Awaji*, 399-402, 2009
1508. A. Takamatsu, R. Okamoto, M. Ito, and T. Gomi, Adaptation by environment-dependent-dynamical network in Physarum, *Proceedings of 4th International Symposium on Mobilitance in Awaji*, 357-361, 2009
1509. M. Uemura, S. Kawamura, Resonance-based Motion Control Method for Multi-Joint Robot through Combining Stiffness Adaptation and Iterative Learning Control, *Proc. of the 2009 IEEE International Conference on Robotics and Automation (ICRA 2009)*, 1543-1548, 2009
1510. Sadao Kawamura, New Aspects of Iterative Learning Control, *Proc. of the ICROS-SICE International Joint Conference 2009 (ICROS-SICE 2009)*, 3083-3088, 2009
1511. Masahiro Sekimoto, Soguru Arimoto, Boris I. Pritulsky, Tadao Isaka, and Sadao Kawamura, Observation of human multi-joint arm movement from the viewpoint of a Riemannian distance, *Proc. of the ICROS-SICE International Joint Conference 2009 (ICROS-SICE 2009)*, 2664-2669, 2009
1512. Masahiro Sekimoto, Sadao Kawamura, Tomoya Ishitsubo, Shinsuke Akizuki, and Masayuki Mizuno, Posture control of a multi-joint robot based on composition of feedforward joint-torques acquired by iterative learning, *Proc. of the ICROS-SICE International Joint Conference 2009 (ICROS-SICE 2009)*, 3094-3099, 2009
1513. M. Uemura, S. Kawamura, Adaptive Tuning of Stiffness and Motion for Multi-Joint Robot, *Proc. of the 9th International IFAC Symposium on Robot Control (SYROCO 2009)*, 607-612, 2009
1514. Masahiro Sekimoto, Soguru Arimoto, and Sadao Kawamura, Task-space iterative learning for redundant robots: Simultaneous acquisitions of desired motion and force trajectories under constraints, *Proc. of the 9th International IFAC Symposium on Robot Control (SYROCO 2009)*, 613-618, 2009
1515. M. Uemura, K. Kimura, S. Kawamura, Generation of Energy Saving Motion for Biped Walking Robot through Resonance-based Control Method, *Proc. of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2009)*, 2928-2933, 2009
1516. Masahiro Sekimoto, Sadao Kawamura, Tomoya Ishitsubo, Shinsuke Akizuki, and Masayuki Mizuno, Basis-motion torque composition approach: Generation of feedforward inputs for control of multi-joint robots, *Proc. of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2009)*, 3127-3132, 2009
1517. Sadao Kawamura, Yuuji Hayashi, Takashi Mitsuda, Misunori Uemura, Masahiro Sekimoto, Tadao Isaka, Stability Conditions of Feedback Robot Motion Control Based on Linear Transformation from Vision to Motion, *Proc. of the 3rd International Symposium on Mobilitance in Awaji*, 387-392, 2009
1518. Takashi Mitsuda, Sadao Kawamura, Misunori Uemura, Masahiro Sekimoto, Role of bi-articular muscles in linearized joint kinematics, *Proc. of the 3rd International Symposium on Mobilitance in Awaji*, 403-408, 2009

## Awards

### ● 2005

1. 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems Best Paper Award: "Don't Try to Control Everything!: An Emergent Morphology Control of a Modular Robot", Akio Ishiguro, Masahiro Shimizu, and Toshihiro Kawakatsu
2. Best Paper Award to the IEEE International Workshop on Robot and Human Interactive Communication 2004 (RO-MAN 2004) in Kurashiki, Japan (Awarded on 14th, August, 2005) : "Deskwork Support System Based on the Estimation of Human Intentions," Yusuke Tamura, Masao Sugi, Jun Ota and Tamio Arai

### ● 2006

3. Masashi Ito and Masafumi Yano 4th joint meeting of ASA/ASJ, 28 November–2 December 2006, Honolulu, Hawaii, The second place winner of the Best Student Paper in Speech Communication, "Pitch determination and sinusoidal modeling for time-varying voiced speech," J. Acoust. Soc. Am 120(5), pp. 3376.
4. Yasuaki Kuroe and Hitoshi Ima : World Congress of Computational Intelligence, Best Session Paper Award, A Learning Method for Synthesizing Spiking Neural Oscillators, July 20, 2006, Proc. of International Joint Conference on Neural Networks, pp.7613-7617, 2006
5. Takuya Umedachi, Akio Ishiguro: 2006 IEEE Robotics and Automation Society Japan Chapter Young Award (IROS) 「Development of a Fully Self-contained Real-time Tunable Spring」.2006年10月11日 Proc. of 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, WP2-6(3), 2006

### ● 2007

6. Masashi Ito and Masafumi Yano, 19th international congress on acoustics, 2-7 September 2007, Madrid, Spain/Young Scientist Conference Attendance Grant in 19th international congress on acoustics" Articulatory feature estimation for nonstationary vowels based on a local vector coding."
7. Sakurai T, Uchino K, Sezutsu H, Tamura T and Kanzaki R: 4th Asia-Pacific Conference on Chemical Ecology Best Poster Award "Axonal projections of pheromone receptor neurons to the antennal lobe macroglomerular complex in the silkworm, *Bombyx mori*." (Epcal Tsukuba, Tsukuba, Japan, Sep 10-14)
8. Tadahiro Taniguchi, Kenji Ogawa, and Tetsuo Sawaragi, "Implicit estimation of other's intention without direct observation of actions in a collaborative task: Situation-Sensitive Reinforcement Learning", SICE Annual Conference 2007, in CD-ROM, (2007) SICE Annual Conference 2007 International Award Finalist

### ● 2008

9. Hitoshi Aonuma, Zoological Science Award 2008. The Zoological Society of Japan 「Tsuji E., Aonuma H., Yokohari F. and Nishikawa M. (2007) Serotonin-immunoreactive neurons in the antennal sensory system of the brain in the carpenter ant, *Camponotus japonicus*. Zool. Sci., 24: 836-849.」
10. Dai Owaki, Koichi Osuka and Akio Ishiguro : ICRA2008, IEEE Robotics and Automation Society Japan Chapter Young Award, "On the Embodiment That Enables Passive Dynamic Bipedal Running", May 19-23, 2008, 2008 IEEE International Conference on Robotics and Automation proceedings, pp 341-346, 2008
11. Dai Owaki, Koichi Osuka, Akio Ishiguro: SICE Annual Conference Young Author's Award of the SICE2008, "Gait Transition between Passive Dynamic Walking and Running by Changing the Body Elasticity", August 20-22, 2008, SICE Annual Conference 2008, pp 2513-2518, 2008
12. Dai Owaki, Koichi Osuka, Akio Ishiguro : Finalist in the SICE Annual Conference International Award, "Gait Transition between Passive Dynamic Walking and Running by Changing the Body Elasticity", August 20-22, 2008, SICE Annual Conference 2008, pp 2513-2518, 2008
13. Toshiyuki Nakagaki, Hiroyasu Yamada, Ryo Kobayashi, Atsushi Tero, Akio Ishiguro, Ágotá Tóth : 2008 Ig Nobel Prize (Cognitive Science Prize) , For discovering that slime molds can solve puzzles, October 2, 2008
14. Masahiro Sekimoto, Suguru Arimoto, Sadao Kawamura, and Ji-Hun Bae: 2008 IEEE International Conference on Robotics and Automation (ICRA2008), Best Manipulation Paper Award Finalist, "Skilled-Motion Plannings of Multi-Body Systems Based upon Riemannian Distance," Proc. of the ICRA2008, pp.1233-1238, Pasadena, CA, USA, May 19-23, 2008.

### ● 2009

15. Yoshikatsu Hayashi, Young Author Award at the 14th International Symposium on Artificial Life and Robotics, Oita, Japan, February 5-7, 2009
16. Q. An, 2009 IEEE Int. Conf. on Mechatronics and Automation (ICMA 09), Best Student Paper Award, Q. An, H. Matsuoka, Y. Ikemoto, H. Asama: "Extraction of Behavior Primitives for Understanding Human Standing-up Motion", Proc. of 2009 IEEE Int. Conf. on Mechatronics and Automation (ICMA 09), pp. 1800-1805, Changchun, China, Aug. (2009).
17. Ji-Soo Keum, Hyon-Soo Lee, Masafumi Hagiwara: Best paper award in International Symposium on Advanced Intelligent Systems (ISIS 2009), "A novel speech/music discrimination using feature dimensionality reduction," International Symposium on Advanced Intelligent Systems (ISIS 2009), pp.129-132, 2009-08.
18. Masahiro Shimizu and Akio Ishiguro : IROS 2009, The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, Best Paper Finalist, An Amoeboid Modular Robot That Exhibits Real-time Adaptive Reconfiguration, 2009/10/14, IROS2009, Molli14.3 pp.1496-1501, 2009

## Patent

### ● 2008

1. S. Kakei, J. Lee, Y. Kagamihara, international patent, applied, 2008.8.26, PCT/JP2008/053735

# Activity Records

See the project homepage ([http://www.race.u-tokyo.ac.jp/~ota/mobiligence/act/index\\_e.html](http://www.race.u-tokyo.ac.jp/~ota/mobiligence/act/index_e.html)) for detailed information.

- 2005
- 1 Date: March 8th, 2006  
Place: Kashiwa New Campus, The University of Tokyo  
Title: IAS-9 (Intelligent Autonomous Systems-9) Organized Session
  - 2 Date: December 4th, 2005  
Place: Conference Hall, Hokkaido University  
Title: Mobiligence'05 (Internatinal Symposium)
- 2006
- 1 Date: April 10th, 2006  
Place: Room 316, Bld. P, University of Electro-Communications  
Subject: Explanation about walking control using CPGs and mobiligence activity for media
  - 2 Date: April 24th, 2006  
Place: Room 321, Bld.14, Faculty of Engineering, The Univ. of Tokyo  
Subject: A group general meeting
  - 3 Date: April 27-28th, 2006  
Place: Nagoya University  
Subject: D group meeting (planned research groups)
  - 4 Date: May 18th, 2006  
Place: Dept. of Mechanical Engineering, Kobe University  
Subject: D group meeting (planned research groups)
  - 5 Date: May 21st, 2006  
Place: Research Institute for Electronic Science, Hokkaido University  
Subject: 1st C group general meeting
  - 6 Date: June 9th, 2006  
Place: Asahikawa Medical College  
Subject: Study session on Biology-Engineering integrating research
  - 7 Date: June 10th, 2006  
Place: Campus Plaza Kyoto  
Subject: 1st D group general meeting
  - 8 Date: June 23rd-25th, 2006  
Place: Toya SunPalace, Hokkaido  
Subject: Mobiligence Symposium
  - 9 Date: July 21st, 2006  
Place: Research Institute for Electronic Science, Hokkaido University  
Subject: C group study session
  - 10 Date: July 22nd, 2006  
Place: Kyoto University  
Subject: 3rd B group general meeting
  - 11 Date: September 4th, 2006  
Place: Tokyo Institute of Technology  
Subject: 1st Mobiligence Engineering Seminar "Measurement and Signal Processing Seminar"
  - 12 Date: September 14th, 2006  
Place: Tsuyama Campus, Okayama University  
Subject: Organized Session "Mobiligence" in The 24th Annual Conference of the Robotics Society of Japan (in Japanese)
  - 13 Date: September 18th, 2006  
Place: Shikotsuko lake  
Subject: C group study session on social behaviors in insects
  - 14 Date: September 26th, 2006  
Place: RACE (Research into Artifacts, Center for Engineering), The University of Tokyo  
Subject: Organized session "Mobiligence" in the 16th Intelligent Systems Symposium (FAN Symposium) (in Japanese)
  - 15 Date: September 28th, 2006  
Place: Okubo Campus, Waseda University  
Subject: 3rd D group general meeting
  - 16 Date: October 11th, 2006  
Place: Beijing, China  
Subject: Organized session "Mobiligence" in IEEE/RSJ International Conference on Intelligent Robots and Systems 2006
  - 17 Date: October 31st, 2006  
Place: DIST - University of Genova, Italy  
Subject: Seminar
  - 18 Date: November 20th, 2006  
Place: Research Institute of Electrical Communication, Tohoku University  
Subject: A & B group joint meeting
  - 19 Date: November 21st, 2006  
Place: BEXCO, Busan, Korea  
Subject: Organized Session "Mobiligence" in SICE-ICASE International Joint Conference 2006 (SICE-ICCAS2006)
  - 20 Date: December 6th, 2006  
Place: Human Information System Laboratory,

Kanazawa Institute of Technology

- Subject: C group study session on cricket modeling
- 21 Date: January 9th, 2007  
Place: KKR Yamaguchi Asakura  
Subject: 4th D group general meeting
- 22 Date: January 29th, 2007  
Place: Tokyo Institute of Technology  
Subject: Organized session "Mobiligence" in SICE 19th SICE Symposium on Decentralized Autonomous Systems (in Japanese)
- 23 Date: February 10th, 2007  
Place: 50th Anniversary Memorial Hall, Ryukyu University  
Subject: C group general meeting

● 2007

1. Date: March 13-14th, 2007  
Place: Dept. of Biomechatronics, TU-Ilmenau  
Name: B group meeting
2. Date: March 15th, 2007  
Place: Locomotion Laboratory, Jena Univ.  
Name: B group meeting
3. Date: March 16th, 2007  
Place: Institute of Sport Science, Jena Univ.  
Name: B group meeting
4. Date: April 4-6th, 2007  
Place: University of Padova, Padova campus and Vicenza campus, Italy  
Name: International Workshop on Mobiligence
5. Date: April 10th, 2007  
Place: University of Zurich  
Name: D group discussion
6. Date: June 14-17th, 2007, 9:00-18:00  
Place: Universidade Tecnica di Lisboa, Portugal  
Name: The 3rd International Symposium on Measurement, Analysis and Modeling of Human Functions (ISHF2007)
7. Date: July 13th, 2007, 14:00~16:00  
Place: Salvador, Brazil  
Name: Organized Session: Multidisciplinary approaches for understanding the adaptive behavior in insects (Chairs: H. Aonuma, R. Kanzaki)  
Artificial model for behavior switching by using network transition through neuro modulation effect. Kurabayashi, D. (Tokyo Institute of Technology)  
Insect-machine hybrid systems for analyzing adaptive behaviors, Kanzaki, R. (University of Tokyo)  
Brain NOS activity regulates reproductive state-related behaviors in grasshoppers. Heinrich R. (University Goettingen, Germany)  
NO/cGMP system and biogenic amine system in agonistic behavior in the cricket. Aonuma H., Hokkaido University, Japan.  
A neuroanatomical guide of the cercal scape system

of the wood cricket. Insausti, T. Universiteacute Franccedil;ois Rabelais, France.

8. Date: July 16-20th, 2007, 8:45~17:00  
Place: ETH Zurich, University of Zurich  
Name: ICIAM07 (6th International Congress on Industrial and Applied Mathematics)
9. Date: July 18-20th, 2007, 13:30~12:00  
Place: Awaji, Hyogo, Japan  
Name: The second International Symposium on Mobiligence
10. Date: November 7-12th, 2007, 14:00~11:00  
Place: University of Montevideo, Uruguay  
Name: NEURAL CODING 2007
11. Date: November 17-21th, 2007, 8:30-12:30  
Place: East China University of Science & Technology Convention Center, Shanghai, China  
Name: ICCN'07 & SICPB'07

● 2008

1. Date: 2008/3/17 9:00-19:00  
Place: National Institute for Physiological Science, JAPAN  
Subject: 5th research discussion and experiment
2. Date: 2008/4/7 9:00-19:00  
Place: National Institute for Physiological Science, JAPAN  
Subject: 6th research discussion and experiment
3. Date: 2008/4/14-16  
Place: Fukushima Medical University  
Subject: Cooperative experiment to measure volume of discharge of GABA at PPN
4. Date: 2008/4/15-16 10:00-17:00  
Place: The University of Tokyo  
Subject: D-group meeting
5. Date: 2008/4/15-16 10:00-17:00  
Place: Kanazawa University  
Subject: Mobiligence seminar on butterflies
6. Date: 2008/4/18-19  
Place: School of Human Science and Environment, University of Hyogo  
Subject: International Seminar on Social Insects
7. Date: 2008/4/19 13:00-4/20 12:00  
Place: Yamaguchi University  
Subject: Seminar on CPG
8. Date: 2008/4/25  
Place: Auditorium, 11th bld., F.o.E., The University of Tokyo  
Subject: Workshop on Mobiligence, "New Development of Mobiligence"
9. Date: 2008/4/25 12:00-22:00  
Place: School of Human Science and Environment, University of Hyogo  
Subject: Research discussion
10. Date: 2008/4/26 9:00-19:00  
Place: School of Human Science and Environment, University of Hyogo  
Subject: Cooperative preliminary experiment for measurement of CO2 density in nest box of hunnybees.
11. Date: 2008/4/28 10:00-17:00

- Place: The University of Tokyo  
Subject: Workshop on Mobiligence  
12 Date: 2008/4/28 12:00-18:00  
Place: Yamaoka Lab., Kyoto Institute of Technology  
Subject: Research meeting on Crickets  
13 Date: 2008/5/12-15 9:00-17:00  
Place: Asahikawa Medical College  
Subject: Research discussion on how to record brainstem region in monkey walking  
14 Date: 2008/5/20-21 9:00-17:00  
Place: Asahikawa Medical College  
Subject: Research discussion on how to record brainstem region in monkey walking  
15 Date: 2008/6/3 8:30-19:30  
Place: Case Western Reserve University, Cleveland, Ohio, USA  
Subject: OS "Mobiligence" at 4th International Symposium on Adaptive Motion of Animals and Machines  
16 Date: 2008/6/5 10:00-16:00  
Place: Big Hat, Nagano, Japan  
Subject: Mobiligence tutorial session: "From Cognition to Emergence of Locomotion and Behavior" in ROBOMECH2008  
17 Date: 2008/6/9 13:00-20:00  
Place: Human Information System Laboratories, Kanazawa Institute of Technology  
Subject: Research meeting on Crickets  
18 Date: 2008/6/13 12:00-13:00  
Place: Lobby of Kyoto Station Hotel  
Subject: 7th Research disucussion  
19 Date: 2008/6/16 18:00-20:00  
Place: Video discussion  
Subject: Seminar  
20 Date: 2008/6/18-19 10:00-17:00  
Place: Osaka Prefecture University, Kyoto University  
Subject: Mobiligence Seminar on Butterflies and Photographing experiment  
21 Date: 2008/6/23 18:00-20:00  
Place: Video discussion  
Subject: Seminar  
22 Date: 2008/6/28 9:30~17:00  
Place: Die Eidgenossische Technische Hochschule Zurich  
Subject: International Workshop on "Control of locomotion: from animals to robots"  
23 Date: 2008/6/30-7/5 13:00-19:00  
Place: School of Human Science and Environment, University of Hyogo  
Subject: Cooperative experiments on dancing behavior of hunnybees  
24 Date: 2008/7/4 18:00-20:00  
Place: Video discussion  
Subject: Seminar  
25 Date: 2008/7/11-12  
Place: Kansai Seminar House, Kyoto  
Subject: International Workshop on "Agency"  
26 Date: 2008/7/15 18:00-20:00  
Place: Video discussion  
Subject: Seminar  
27 Date: 2008/7/22-23 13:00-18:00  
Place: Research Institute of Electronic Science, Hokkaido University  
Subject: Collaborative group meeting  
28 Date: 2008/7/25 18:00-20:00  
Place: Video discussion  
Subject: Seminar  
29 Date: 2008/8/6-7 9:00-19:00  
Place: School of Human Science and Environment, University of Hyogo  
Subject: Cooperative experiment on hunnybee's behavior  
30 Date: 2008/8/6 16:00-17:30  
Place: Seminar room, RACE, The University of Tokyo  
Subject: Research meeting on Mobiligence  
31 Date: 2008/8/12 13:00-18:00  
Place: Osaka University  
Subject: Research discussion on how to record brainstem region in monkey walking  
32 Date: 2008/8/18 17:00-19:00  
Place: University of Hyogo/Tokushima Bunri University (Video discussion)  
Subject: Seimar and research discussion  
33 Date: 2008/8/21 13:15-15:15  
Place: The University of Electro-Communication  
Subject: SICE Annual Conference Organized Session OS "Biomimetic Approach on Robot Design and Control for Dynamic Locomotion"  
34 Date: 2008/8/22 10:00~16:00  
Place: Body Motion Science Laboratory, The University of Tokyo  
Subject: B-group meeting  
35 Date: 2008/8/24-26 12:00-17:00  
Place: Asahikawa Medical College  
Subject: 1st research discussion on biped walking model  
36 Date: 2008/8/28 13:00-16:00  
Place: Ishiguro laboratory, Tohoku University  
Subject: Research discussion on self-assembly system  
37 Date: 2008/9/13 10:00-12:00  
Place: University of Hyogo/Tokushima Bunri University (Video discussion)  
Subject: Seimar and research discussion  
38 Date: 2008/9/10 12:30-14:30  
Place: Faculty of Engineering, Kobe University  
Subject: The 26th Annual Conference on Japan Robotics Society (RSJ2008), Session "Mobiligence"  
39 Date: 2008/9/15 14:30-2008/9/7 13:00  
Place: Design gallery, Asahikawa KURAIMU  
Subject: Research meeting on neurobiology on invertebrate  
40 Date: 2008/9/17  
Place: Osaka University  
Subject: B03 group meeting  
41 Date: 2008/9/20 13:00-15:00  
Place: University of Hyogo/Tokushima Bunri University (Video discussion)  
Subject: Seimar and research discussion  
42 Date: 2008/9/22 14:00~17:00

- Place: National Rehabilitation Center for Persons with Disabilities  
Subject: Seminar on Bipedal Walking Control  
43 Date: 2008/9/25-10/7 9:00-19:00  
Place: School of Human Science and Environment, University of Hyogo  
Subject: Cooperative experiment on honeybee's behavior in the nest  
44 Date: 2008/9/25 11:00-14:00  
Place: Ishiguro laboratory, Tohoku University  
Subject: Research discussion on self-assembly system  
45 Date: 2008/9/25 19:30-21:00  
Place: University of Hyogo/Tokushima Bunri University (Video discussion)  
Subject: Seimar and research discussion  
46 Date: 2008/9/26 9:00-18:00  
Place: Acropolis Convention Center, Nice, France  
Subject: IROS2008 Full Day Workshop  
47 Date: 2008/10/1-2  
Place: The University of Tokyo, Komaba Campus  
Subject: Workshop on "Artificial Life: Half way through"  
48 Date: 2008/10/9-10 10:00-16:00, 10:00-14:00  
Place: Asahikawa Medical College  
Subject: 2nd research discussion on biped walking model  
49 Date: 2008/10/10 13:30~18:00  
Place: Wind-tunnel laboratory, Kyoto University  
Subject: Bibliographic survey and discussion  
50 Date: 2008/10/14-16 9:00-19:00  
Place: Fukushima Medical University  
Subject: Cooperative experiment to measure volume of discharge of GABA at PPN  
51 Date: 2008/10/14 18:30-20:00  
Place: University of Hyogo/Tokushima Bunri University (Video discussion)  
Subject: Seimar and research discussion  
52 Date: 2008/10/15 9:30-12:00  
Place: Kyoto Institute of Technology  
Subject: Research discussion on collaborative research  
53 Date: 2008/10/17 13:30~18:00  
Place: Kyotanabe Campus, Doshisha University  
Subject: Research discussion  
54 Date: 2008/10/21 10:00-17:40  
Place: RACE, The University of Tokyo  
Subject: 2nd Open Symposium on Mobiligence  
55 Date: 2008/10/22 9:30-16:00  
Place: The University of Tokyo  
Subject: D-group meeting  
56 Date: 2008/10/23 18:00-20:00  
Place: University of Hyogo/Tokushima Bunri University (Video discussion)  
Subject: Seimar and research discussion  
57 Date: 2008/10/24 13:30-17:00  
Place: Tohoku University  
Subject: Seminar on Passive Dynamic Walk  
58 Date: 2008/10/24 13:30~18:00  
Place: Kyotanabe Campus, Doshisha University  
Subject: Research discussion  
59 Date: 2008/10/30 13:30~18:00  
Place: Kyotanabe Campus, Doshisha University  
Subject: Research discussion  
60 Date: 2008/10/31 18:30-20:00  
Place: University of Hyogo/Tokushima Bunri University (Video discussion)  
Subject: Seimar and research discussion  
61 Date: 2008/11/6 13:00~18:00, 11/7 10:00~15:30  
Place: National Institute of Informatics  
Subject: 2nd A-group meeting  
62 Date: 2008/11/8 15:00-17:00  
Place: University of Hyogo/Tokushima Bunri University (Video discussion)  
Subject: Seimar and research discussion  
63 Date: 2008/11/7 13:30~18:00  
Place: Kyotanabe Campus, Doshisha University  
Subject: Bibliographic survey and discussion  
64 Date: 2008/11/14-15 10:00-17:00  
Place: Kyushu University  
Subject: Mobiligence seminar on butterflies and Symposium of The Lapidopterological Society of Japan  
65 Date: 2008/11/14 13:30~18:00  
Place: Kyotanabe Campus, Doshisha University  
Subject: Bibliographic survey and discussion  
66 Date: 2008/11/14 17:00-19:00  
Place: University of Hyogo/Tokushima Bunri University (Video discussion)  
Subject: Seimar and research discussion  
67 Date: 2008/11/15 18:00-19:00  
Place: Washington, D.C.  
Subject: 8th research discussion  
68 Date: 2008/11/17 15:15-16:45  
Place: Tsukuba International Congress Center, Tsukuba, Ibaraki, Japan  
Subject: OS "Mobiligence" at The 9th International Symposium on Distributed Autonomous Robotic Systems (DARS2008)  
69 Date: 2008/11/20 11:15-13:00  
Place: Ishiguro laboratory, Tohoku University  
Subject: Research discussion on self-assembly system  
70 Date: 2008/11/21 13:30~18:00  
Place: Wind-tunnel laboratory, Kyoto University  
Subject: Bibliographic survey and discussion  
71 Date: 2008/11/21 13:30-18:00  
Place: Ishiguro laboratory, Tohoku University  
Subject: Research discussion: scaling effect on adaptability of deformed body of slime mold  
72 Date: 2008/11/21 19:00-21:00  
Place: University of Hyogo/Tokushima Bunri University (Video discussion)  
Subject: Seimar and research discussion  
73 Date: 2008/11/26 15:15-17:20  
Place: Himeji International Exchange Center  
Subject: OS "Mobiligence" at SICE System & Information Division: Annual Conference

- 74 Date: 2008/11/27 15:00-17:00 Place: Takamatsu laboratory, Waseda University  
 Place: Ishiguro laboratory, Tohoku University Subject: Research discussion: scaling effect on adaptability of deformed body of slime mold  
 Subject: Research discussion on self-assembly system
- 75 Date: 2008/11/28 13:30~18:00 90 Date: 2009/1/5 13:00-19:00  
 Place: Kyotanabe Campus, Doshisha University Place: Human Information System Laboratories, Kanazawa Institute of Technology  
 Subject: Research discussion Subject: Research discussion on collaborative research
- 76 Date: 2008/12/1 18:00-20:00 91 Date: 2009/1/5 13:00-19:00  
 Place: University of Hyogo/Tokushima Bunri University Place: Human Information System Laboratories, Kanazawa Institute of Technology  
 (Video discussion) Subject: Research discussion on collaborative research
- 77 Date: 2008/12/4 11:00-13:00 92 Date: 2009/1/5 13:30-1/6 11:00  
 Place: Ishiguro laboratory, Tohoku University Place: Awaji Yumebutai, Convention Hall  
 Subject: Research discussion on self-assembly system Subject: Symposium on Walking
- 78 Date: 2008/12/5 10:00-12:00 93 Date: 2009/1/8 18:30-20:00  
 Place: Nagaragawa Convention Center Place: University of Hyogo/Tokushima Bunri University  
 Subject: SICE SI2008, Organized session "Emergence of (Video discussion) Subject: Seimar and research discussion
- 79 Date: 2008/12/5 13:30~18:00 94 Date: 2009/1/9 13:30~18:00  
 Place: Kyotanabe Campus, Doshisha University Place: Kyotanabe campus, Doshisha University  
 Subject: Bibliographic survey and discussion Subject: Research discussion
- 80 Date: 2008/12/11 14:30-16:00 95 Date: 2009/1/12 13:00-17:00  
 Place: Hongo, Tokyo Place: Concert hall, School of Human Science and Environment, University of Hyogo  
 Subject: 9th research discussion Subject: Mobiligence seminar on "Ecological and Physiological Studies about Sociality of Insects"
- 81 Date: 2008/12/15-16 96 Date: 2009/1/13 9:30-18:00  
 Place: The University of Tokyo Place: Concert hall, School of Human Science and Environment, University of Hyogo  
 Subject: Workshop on Informatics of Dynamical Systems Subject: C-group meeting
- 82 Date: 2008/12/16-17 10:00-17:00 97 Date: 2008/1/14 15:00-20:00  
 Place: Osaka Prefecture University Place: Kagawa School of Pharmaceutical Sciences, Tokushima Bunri University  
 Subject: Mobiligence seminar on butterflies Subject: Research discussion on collaborative research
- 83 Date: 2008/12/18 10:00-17:00 98 Date: 2009/1/16 13:30~18:00  
 Place: Tohoku University Place: Kyotanabe campus, Doshisha University  
 Subject: Research discussion Subject: Research discussion
- 84 Date: 2008/12/18 13:00-20:00 99 Date: 2009/1/20 16:00-20:00  
 Place: Laboratory of Physiological Chemistry, The University of Tokyo Place: Faculty of Liberal Arts, Tohoku Gakuin University  
 Subject: Research survey and discussion on measurement of swarm behavior Subject: Research discussion on self-assembly system
- 85 Date: 2008/12/18 14:00-12/19 12:00 100 Date: 2008/1/23 13:00-16:45  
 Place: Research Institute of Electrical Communication, Tohoku University Place: Torigin Bunka Kaikan, Tottori, Japan  
 Subject: Research meeting on RIEC Collaborative Project Research "Understanding and Engineering Application of Environmentally Harmonic Adaptive Systems in Living Things" Subject: OS "Mobiligence" at 21st Symposium on Distributed Autonomous Systems
- 86 Date: 2008/12/19 13:30-17:50 101 Date: 2009/1/28 13:30~18:00  
 Place: Research Institute of Electrical Communication, Tohoku University Place: Kyotanabe campus, Doshisha University  
 Subject: Debate session on locomotive control of animals Subject: Research discussion
- 87 Date: 2008/12/25-26 9:00-19:00 102 Date: 2009/1/28 18:00-20:00  
 Place: Kagawa School of Pharmaceutical Sciences, Tokushima Bunri University Place: University of Hyogo/Tokushima Bunri University  
 Subject: Research discussion (Video discussion) Subject: Seimar and research discussion
- 88 Date: 2008/12/25 13:00-15:00 103 Date: 2009/2/03-04 10:00-17:00  
 Place: Ishiguro laboratory, Tohoku University Place: Hokkaido University  
 Subject: Research discussion on self-assembly system Subject: Mobiligence seminar on Butterflies
- 89 Date: 2008/12/26 13:00-18:00 104 Date: 2009/2/4  
 Place: Ishiguro laboratory, Tohoku University Place: Tokyo Institute of Technology  
 Subject: Research discussion on self-assembly system Subject: Review meeting on textbook publication

- 105 Date: 2009/2/4 17:30-18:30  
Place: The University of Tokyo, Komaba Campus  
Subject: Seminar
- 106 Date: 2009/2/7 13:00-15:00  
Place: University of Hyogo/Tokushima Bunri University  
(Video discussion)  
Subject: Seimar and research discussion
- 107 Date: 2009/2/13-2/19 9:00-19:00  
Place: Research Institute of Electronic Science, Hokkaido University  
Subject: Invitation of foreign researcher and research discussion
- 108 Date: 2009/2/13 13:30~18:00  
Place: Kyotanabe campus, Doshisha University  
Subject: Research discussion
- 109 Date: 2009/2/13 17:00-19:00  
Place: University of Hyogo/Tokushima Bunri University  
(Video discussion)  
Subject: Seimar and research discussion
- 110 Date: 2009/2/18 9:00-20:00  
Place: National Institute for Physiological Science, JAPAN  
Subject: 10th research discussion and cooperative experiment
- 111 Date: 2009/2/18  
Place: Research Institute of Electronic Science, Hokkaido University  
Subject: Invitation of foreign researcher and research discussion
- 112 Date: 2008/2/19 10:30-13:30  
Place: Ishiguro laboratory, Tohoku University  
Subject: Research discussion on self-assembly system
- 113 Date: 2009/3/2 13:40-3/4 12:00  
Place: Hotel Matsushima Taikanso  
Subject: 4th Mobiligence Symposium
- 114 Date: 2009/3/11 13:30-17:30  
Place: Waseda University  
Subject: 6th collaborative seminar of SICE research group of "biological control system" and "mobiligence"
- 2009
- 1 Date: 2009/1/5 13:00~19:00  
Place: Concert hall, School of Human Science and Environment, University of Hyogo  
Subject: Verification of progress and discussion
- 2 Date: 2009/1/12 13:00~17:00  
Place: Research Institute of Electronic Science, Hokkaido University  
Subject: Talk by Prof. Ken Lukowiak (Calgary Univ.) and discussion
- 3 Date: 2009/1/13 9:30~18:00  
Place: Research Institute of Electronic Science, Hokkaido University  
Subject: Talk by Prof. Ken Lukowiak (Calgary Univ.), discussion and seminar
- 4 Date: 2009/1/14 15:00~20:00  
Place: Human Information System Laboratories, Kanazawa
- Institute of Technology  
Subject: Research discussion
- 5 Date: 2009/2/13~19 9:00~19:00  
Place: Tokushima Bunri University  
Subject: Research discussion
- 6 Date: 2009/2/18 17:00~16:30  
Place: National Institute for Physiological Science, JAPAN  
Subject: Research Discussion and Experiment
- 7 Date: 2009/2/18 09:00~20:00  
Place: Tokushima Bunri University  
Subject: Discussion and preliminary experiments on polarization vision of honeybee
- 8 Date: 2009/3/27 09:00~20:00  
Place: Tsukuba University  
Subject: Research presentation of Mobiligence on Ethology and Robotics
- 9 Date: 2009/4/13 13:00~17:00  
Place: Tsukuba University  
Subject: Research presentation of Mobiligence on Ethology and Robotics
- 10 Date: 2009/4/30 12:00~18:00  
Place: Tokyo Institute of Technology  
Subject: Research discussion on behavioral analysis of crickets
- 11 Date: 2009/6/2~5 16:00~12:00  
Place: Research Institute of Electronic Science, Hokkaido University  
Subject: Discussion on development of tool for analysis of crickets' social behavior
- 12 Date: 2009/6/3 10:30~17:00  
Place: Ishigaki Island  
Subject: Ecological investigation of crickets and research discussion
- 13 Date: 2009/6/10 14:00~16:00  
Place: Research Institute of Electronic Science, Hokkaido University  
Subject: Verification of research outcomes and discussion on editing of a textbook
- 14 Date: 2009/7/3 10:00~18:00  
Place: Faculty of Engineering, Hokkaido University  
Subject: Verification of research outcomes and discussion on editing of a textbook
- 15 Date: 2009/7/6 13:00~18:00  
Place: Faculty of Engineering, Hokkaido University  
Subject: Announcement of results and verification of progress
- 16 Date: 2009/7/28 09:00~19:00  
Place: Faculty of Engineering, Hokkaido University  
Subject: Research on environmental factor triggering crickets' fighting behavior
- 17 Date: 2009/7/30 12:00~18:00  
Place: Human Information System Laboratories, Kanazawa

Institute of Technology

Subject: Talk by Prof. Ueda (Iowa University)

- 18 Date: 2009/8/4~12 9:00~20:00  
Place: Keio University  
Subject: Visualization of crickets' brain circuit by Gene gun
- 19 Date: 2009/8/4 09:00~20:00  
Place: Research Institute of Electronic Science, Hokkaido University  
Subject: Group meeting and research seminar
- 20 Date: 2009/8/5 09:00~21:00  
Place: National Institute for Physiological Science, JAPAN  
Subject: Research Discussion and Experiment
- 21 Date: 2009/8/6 10:00~18:00  
Place: The University of Tokyo  
Subject: Research Discussion
- 22 Date: 2009/8/6  
Place: 09:00~12:00  
Subject: The University of Tokyo
- 23 Date: Research Discussion and Experiment  
Place: 2009/9/8 14:00~19:00  
Subject: National Institute for Physiological Science, JAPAN
- 24 Date: Research Discussion and Experiment  
Place: 2009/11/23 16:30~19:00  
Subject: National Institute for Physiological Science, JAPAN
- 25 Date: Research Discussion and Experiment  
Place: 2009/11/23 16:30~19:00  
Subject: National Institute for Physiological Science, JAPAN
- 26 Date: Research Discussion and Experiment  
Place: 2009/12/2 18:00~20:00  
Subject: National Institute for Physiological Science, JAPAN
- 27 Date: Research Discussion and Experiment  
Place: 2009/12/18~19 13:00~18:00, 9 : 00~12 : 00  
Subject: Kyoto
- 28 Date: Research Discussion  
Place: 2010/1/19 10:00~16:00  
Subject: Electrocommunication Lab. Tohoku University
- 29 Date: Discussion on Terminus ad quem and direction of Mobiligence  
Place: 2010/2/1 10:00~18:00  
Subject: Osaka University