Neural Computation Unit

Professor Kenji Doya

Abstract

The dual goals of Neural Computation Unit are to elucidate the brain's mechanisms for robust and flexible adaptation and to create autonomous adaptive systems like animals and humans. Our major subject is "reinforcement learning," in which an agent, biological or artificial, learns novel behaviors by active exploration and reward feedback. We now set our focus on "mental simulation," in a subject uses an internal dynamic model of the world to estimate the current state from past state and actions or plan ahead sequence of actions to reach to a desired state. We combine top-down, theoretical approaches and bottom-up, experimental approaches to achieve these goals. Our Unit consists of three groups, neurobiology, computation, and robotics, working on the following topics in a synergistic way.

The Systems Neurobiology Group aims to clarify the neural mechanisms of reinforcement learning and mental simulation through rodent experiments. We revealed working-memory representations in cortico- basal ganglia circuit during decision making tasks (Yoshizawa et al., 2023). Our prism-lens imaging showed differential coding of prediction and actual sensory signal in deep and superficial layers of the somatosensory cortex. We started to analyze the activities of dorsal raphe serotonin neurons during behaviors to obtain reward and to avoid punishment.

The Dynamical Systems Group develops methods for neural data analysis and construct models of the functions and dysfunctions of the brain. We participated in Japan's flagship neuroscience project, Brain/MINDS, we analyzed the wide-field calcium imaging data and further extended the optical neuroimage analysis tool OptiNiSt (https://optinist.readthedocs.io).

The Adaptive Systems Group develop robust and efficient learning algorithms and test them in simulation and robotic experiments. We developed novel reinforcement learning algorithms and smartphone-based platform for evolutionary robotics.

We have been successful in obtaining external funding, Kakenhi in Transformative Areas (FY2023-2027) and Brain/MINDS 2.0 (FY2023-2028). We also contributed to the visibility of OIST in the national and international research community, for example, giving a keynote talk at IJCNN 2023.

1. Staff

SYSTEMS NEUROBIOLOGY GROUP

- Katsuhiko Miyazaki, Senior Staff Scientist
- Kayoko Miyazaki, Senior Staff Scientist
- Anupama Chaudhary, Technician
- Hajime Yamanaka, Technician
- Sergey Zobnin, OIST Student
- Miles Desforges, OIST Student
- Yuma Kajihara, OIST Student
- Jianning Chen, OIST Student
- Naohiro Yamauchi, OIST Student
- Tomohiko Yoshizawa, Visiting Researcher (Hokkaido University)
- Kazumi Kasahara, Visiting Researcher (AIST)

DYNAMICAL SYSTEMS GROUP

- Yukako Yamane, Staff Scientist
- Soheil Keshmiri, Staff Scientist
- Yuzhe Li, Postdoctoral Scholar
- Razvan Gamanut, Research Fellow
- Florian Lalande, OIST Student
- Shuhei Hara, OIST Student
- Hideyuki Yoshimura, OIST Student
- Sutashu Tomonaga, OIST Student
- Yi-Shan Cheng, OIST Student
- Yusaku Kasai, OIST Student
- Hiroaki Hamada, Visiting Researcher (ARAYA)
- Hiromichi Tsukada, Visiting Researcher (Chubu University)
- Carlos Enrique Gutierrez, Visiting Researcher (Softbank)

ADAPTIVE SYSTEMS GROUP

- Ekaterina Sangati, Postdoctoral Scholar
- Christopher Buckley, Technician
- Kristine Faith Roque, OIST Student
- Yuji Kanagawa, OIST Student
- Tojoarisoa Rakotoaritina, OIST Student

- Farzana Rahman, Visiting Researcher (Independent University)

RESEARCH UNIT ADMINISTRATORS

- Kikuko Matsuo
- Misuzu Saito

2. Collaborations

- Dr. Takuya Isomura at RIKEN CBS and other collaborators in the Unified Theory project.
- Prof. Masanori Matsuzaki and Dr. Teppei Ebina at the University of Tokyo and RIKEN Center for Brain Science for the analysis of the calcium imaging data of the marmoset brain under Brain/MINDS project.
- Prof. Benoit Girard at Sorbonne University and Kim Blackwell at George Mason University on the models of the basal ganglia.
- Our alumni Dr. Dongqi Han at Microsoft Shanghai
- An industrial collaboratory research project on brian-like computation.
- An industrial collaboratory research project on the analysis and modeling of health-related data from wearable devices.

3. Activities and Findings

3.1 Nuerobiology Experiments [Systems Neurobilogy Group]

3.1.1 Neural substrate of dynamic Bayesian inference [Kakenhi Project on Unified Theory]

We continued our experiments to clarify how predictive information from actions and sensory information through environmental interaction are integrated across different layers of the somatosensory and motor cortical circuits in mice. We performed cross-layer calcium imaging while mice performed a lever pulling task with variable lever resistance. Regression analysis showed that more deep layer neurons encode expected lever resistance, while more superficial layer neurons encode actual lever resistance (Zobnin, PhD thesis, 2024). This is a first step toward understanding the cortical implementation of Bayesian inference.

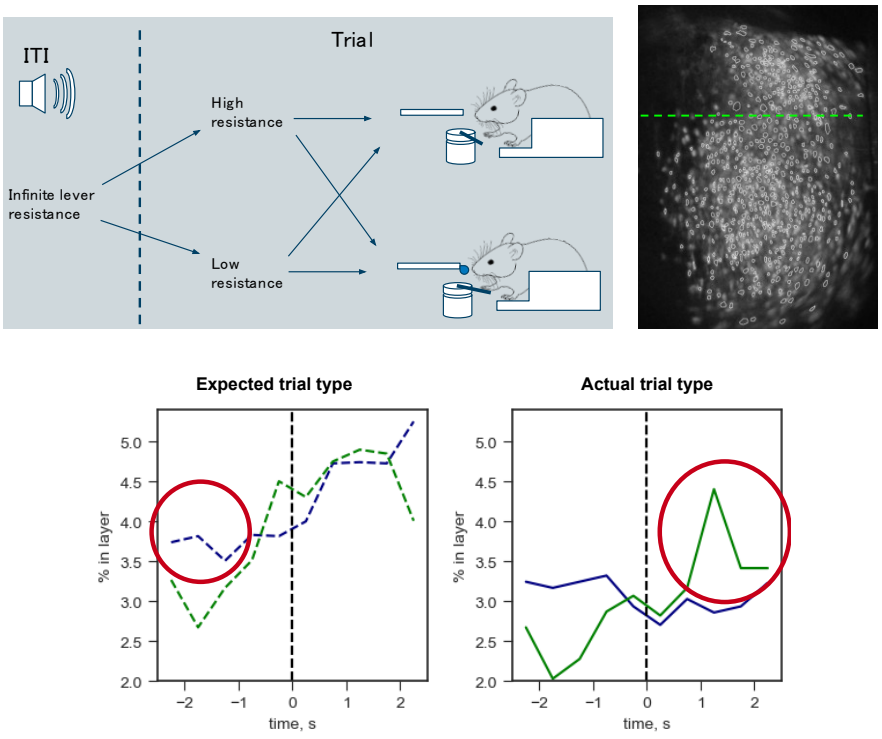

Figure 1: Prism lens imaging of somatosensory cortex in variable-resistance lever pull task (Zobnin, PhD thesis, 2024).

Our paper on the working memory of previous action and reward in the cortico-basal ganglia circuit was published in eNeuro (Yohizawa et al., 2023).

3.1.2 The role of serotonin in the regulation of patience [Moonshot Goal 9]

Under the Moonshot Program, we performed extensive experiments on the roles of serotonin and dopamine in motor actions and patient waiting to obtain rewards and to avoid punishments. Using fiber-photometry, we showed that the activities of serotonin neurons in the dorsal raphe nucleus during waiting is proportional to the probability of reward but not the expected value.

Our paper on the awake opto-fMRI study showing that stimulation of dorsal raphe serotonin neurons activates wide brain areas related to reward prediction was accepted in Nature Communications (Hamada et al., 2024).

3.2. Neural Data Analysis and Modeling [Dynamical Systems Group]

3.2.1 Analysis and modeling of marmoset brain data [Brain/MINDS Project]

We analyzed wide-field calcium imaging data from the premotor to parietal cortex of marmoset monkeys acquired in Matsuzaki lab in University of Tokyo (Ebina et al., 2024). In order to characterize the calcium responses of wide cortical fields, we applied non-negative matrix factorization (NMF) to the fluorescence signal and detected tens of components from the premotor cortex (PM), primary motor cortex (M1), primary somatosensory cortex (S1), and the parietal cortex (PPC). Then to analyze dynamic interactions across these neural populations, we applied the embedding entropy (EE) method (Shi et al., 2022) and found that the causal interactions across populations strengthened through lever push/pull task training.

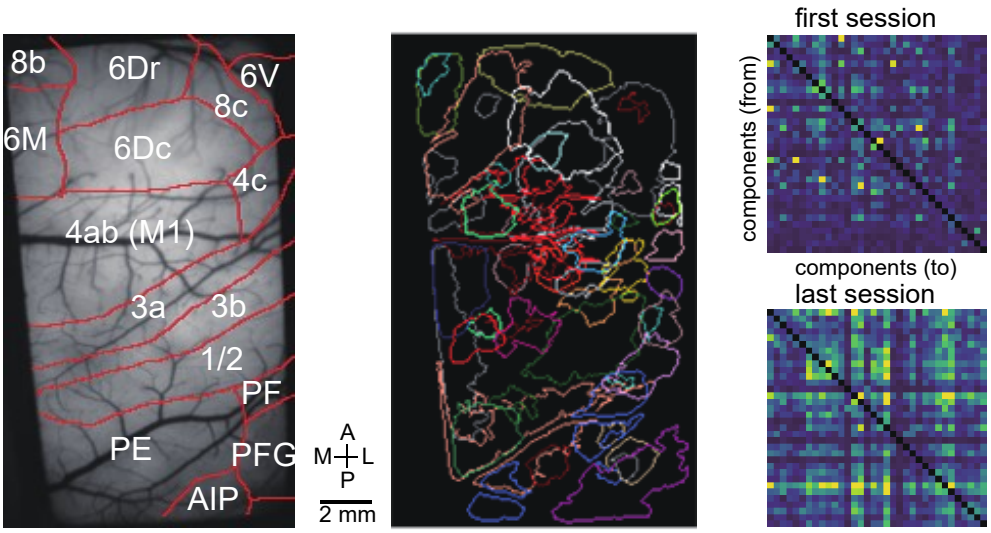

Figure 2: Extraction of distinct spatiotemporal components by NMF from wide-filed calcium imaging from the marmoset cortex. Analysis by embedding entropy showed stronger causal

We continued improving the software OptiNiSt, the optical neuroimage studio, which allows intuitive construction of data processing pipeline by graphic user interface and large-scale processing on PC clusters (https://optinist.readthedocs.io). The open-source software is available from GitHub and DockerHub.

3.2.2 Analysis of wearable device data

We analyzed the physiological data obtained by a wearable device VitalPatch and proposed the transfer entropy from the respiration rate to the heart rate as a new biomarker for health (Keshmiri et al., 2024).

3.3 Robotics and Reinforcement Learning [Adaptive Systems Group]

3.3.1 Data-efficient reinforcement learning

Our paper on how model-free and model-based learning and control can help each other was accepted for publication in Nature Communications (Han et al. 2024).

3.3.2 Smartphone robot platform

We built a new generation of smartphone robots using originally designed circuit boards for improved energy management.

4. Publications

4.1 Journals

1. Blackwell KT, Doya K (2023). Enhancing reinforcement learning models by including direct and indirect pathways improves performance on striatal dependent tasks. *PLoS Comput Biol*, 19, e1011385. https://doi.org/10.1371/journal.pcbi.1011385
2. Hata J, Nakae K, Tsukada H, Woodward A, Haga Y, Iida M, Uematsu A, Seki F, Ichinohe N, Gong R, Kaneko T, Yoshimaru D, Watakabe A, Abe H, Tani T, Hamda HT, Gutierrez CE, Skibbe H, Maeda M, Papazian F, Hagiya K, Kishi N, Ishii S, Doya K, Shimogori T, Yamamori T, Tanaka K, Okano HJ, Okano H (2023). Multi-modal brain magnetic resonance imaging database covering marmosets with a wide age range. *Scientific Data*, 10.1038/s41597-023-02121-2. https://doi.org/10.1038/s41597-023-02121-2
3. Keshmiri S, Tomonaga S, Mizutani H, Doya K (2024). Respiratory modulation of the heart rate: A potential biomarker of cardiorespiratory function in human. Computers in Biology and Medicine, 173. https://doi.org/10.1016/j.compbiomed.2024.108335
4. Kuniyoshi Y, Kuriyama R, Omura S, Gutierrez CE, Sun Z, Feldotto B, Albanese U, Knoll AC, Yamada T, Hirayama T, Morin FO, Igarashi J, Doya K, Yamazaki T (2023). Embodied bidirectional simulation of a spiking cortico-basal ganglia-cerebellar-thalamic brain model and a mouse musculoskeletal body model distributed across computers including the supercomputer Fugaku. *Frontiers in Neurorobotics*, 17. https://doi.org/10.3389/fnbot.2023.1269848
5. Lalande F, Doya K (2023). Numerical data imputation for multimodal data sets: A probabilistic nearest-neighbor kernel density approach. *Transactions on Machine Learning Research.* https://openreview.net/forum?id=KqR3rgooXb
6. Machida I, Shishikura M, Yamane Y, Sakai K (2024). Representation of Natural Contours by a Neural Population in Monkey V4. *eneuro,* 11. https://doi.org/10.1523/ENEURO.0445-23.2024
7. Skibbe H, Rachmadi MF, Nakae K, Gutierrez CE, Hata J, Tsukada H, Poon C, Schlachter M, Doya K, Majka P, Rosa MGP, Okano H, Yamamori T, Ishii S, Reisert M, Watakabe A (2023). The Brain/MINDS Marmoset Connectivity Resource: An open-access platform for cellular-level tracing and tractography in the primate brain. *PLoS Biology*, 21, e3002158. https://doi.org/10.1371/journal.pbio.3002158
8. Toulkeridou E, Gutierrez CE, Baum D, Doya K, Economo EP (2023). Automated segmentation of insect anatomy from micro-CT images using deep learning. *Natural Sciences*, 10.1002/ntls.20230010. https://doi.org/10.1002/ntls.20230010
9. Yamane Y, Ito J, Joana C, Fujita I, Tamura H, Maldonado PE, Doya K, Grun S (2023). Neuronal Population Activity in Macaque Visual Cortices Dynamically Changes through Repeated Fixations in Active Free Viewing. *eNeuro,* 10. https://doi.org/10.1523/ENEURO.0086-23.2023
10. Yoshizawa T, Ito M, Doya K (2023). Neuronal representation of a working memory-based decision strategy in the motor and prefrontal cortico-basal ganglia loops. *eNeuro*, 10, NEURO.0413-22.2023. https://doi.org/10.1523/ENEURO.0413-22.2023

4.2 Books and other one-time publications

1. Doya K (2023). Computational cognitive models of reinforcement learning. Sin un R (ed.), The Cambridge Handbook of Computational Cognitive Sciences, 739 - 766. Cambridge University Press, https://doi.org/10.1017/9781108755610.026
2. Doya K (2023). Reinforcement learning. In Sun R (ed.), The Cambridge Handbook of Computational Cognitive Sciences, 350-370. Cambridge University Press, https://doi.org/10.1017/9781108755610.013
3. Doya K (2023). Brain Computation: A Hands-on Guidebook.

   https://oist.github.io/BrainComputation/
4. Doya K (2023). Introduction to Scientific Computing. https://oist.github.io/iSciComp

4.3 Oral and Poster Presentations

([NOTE] *Seminars and workshops by OIST faculty/unit members (either with or without other speakers), either at OIST or at other institutions than OIST, should be included in the 4.3 Oral and Poster Presentations.

INVITED LECTURE/SEMINAR

1. Doya K (2023). IBI Symposium Neural data and knowledge sharing: Efforts and cooperation from Asia to the world, CJK Neuroscience Meeting, Zhuhai, China
2. Doya K (2023). Bayesian inference, reinforcement learning, and the cortico-basal ganglia circuit, IJCNN 2023, Online
3. Doya K (2023). Reinforcement learning and Bayesian inference, OIST Computational Neuroscience Course, Online
4. Doya K (2023). Neural Circuits for Reinforcement Learning and Mental Simulation, Computational Cognitive Science Colloquium, Darmstadt, Germany
5. 銅谷賢治(2023). 推定と制御の双対性と感覚運動皮質の正準回路，数学と脳科学の連携に向けたワークショップ,東京都,日本
6. Doya K (2023). Can Robots Find Their Own Reward Functions? IEEE ROSE 2023，東京都,日本
7. Doya K (2023). Panel for Navigating the Future: The Impact of Professional Societies in Shaping Disruptive Technologies such as Generative AI, ICONIP 2023, Changsha, China
8. Miyazaki K (2023) Elucidation of the mechanism of serotonin over optimism and pessimism, Mechanism of Brain and Mind Winter Workshop 2024, Hokkaido, JAPAN
9. 銅谷賢治(2023). コネクトームで脳はどこまでわかるのか，第 129 回日本解剖学会総会，沖縄県,日本
10. Doya K (2023). Bayesian Inference, Reinforcement Learning, and the Cortico-Basal Ganglia Circuit, the 2024 Workshop "Deep Learning: Theory, Applications, and Implications"，東京都,日本

CONFERENCE ORAL/POSTER PRESENTATIONS

1. Hara S, Suzuki K, Murakami A, Majima K, Abdelhack M, Cheng F, Takahashi H, Doya K (2023). Elucidation of the dysfunction in sensory processing in schizophrenia, Computational Psychiatry Conference Dublin, Ireland
2. Yamane Y, Li Y, Doya K (2023). Introduction to Optical Neuroimage Studio (OptiNiSt), CNS 2023, Leipzig, Germany
3. Yamane Y, Ebina T, Sasagawa A, Terada S, Uemura M, Ohki K, Matsuzaki M, Doya K (2023). Change of sensory-motor network revealed by a wide field calcium imaging of marmoset during learning of forelimb movement task, Neuro 2023, Sendai, JAPAN
4. Miles Desforges (2023). Characterisation of spatiotemporal release of dopamine, noradrenaline and serotonin in cortical M2 using genetically encoded neuromodulator indicators. Neuro 2023, Sendai, JAPAN
5. Soheil Keshmiri, Sutashu Tomonaga, Haruo Mizutani, Kenji Doya (2023). Discovery of the Cardiorespiratory Phenotypes by Wearable Bio-signal Monitoring, Neuro 2023, Sendai, JAPAN
6. Chen J (2023). The effect of optogenetic serotonergic activation on sustained motor action in a lever pressing task, Neuro 2023, Sendai, JAPAN
7. 山根ゆか子 (2023). データ解析ソフトウェアを駆使した研究の効率化と再現性の改善 “OptiNiSt”による皮質ニューロンの解析例, 日本神経科学学会2023m 仙台,日本
8. Yuma Kajihara, Paulette Garcia-Andaluz, Katsuhiko Miyazaki, Hiroto Ashitomi, Kazumasa Z. Tanaka, Kenji Doya (2023). The role of serotonergic input to the paraventricular thalamus in reinforcement learning, Neuro 2023, Sendai, JAPAN
9. Daigo Takeuchi, Yuma Kajihara, Takashi Kawai, Kenji Doya, Susumu Tonegawa (2023). Anterior cingulate cortical circuits adjust multistep choice actions based on model-based inference upon receiving negative outcomes, Neuro 2023, Sendai, JAPAN
10. Tatsuki Machida Yukako Yamane Ko Sakai (2023). Representation of contour shape and surface texture, Neuro 2023, Sendai, JAPAN
11. Sutashu Tomonaga, Soheil Keshmiri, Haruo Mizutani, Kenji Doya (2023). A novel approach to capturing multi-time scale dynamics using latent variable modeling, JNNS2023, Tokyo, JAPAN
12. 宮崎勝彦(2023). セロトニンによる報酬待機行動の制御機構. 第 53 回日本神経精神薬理学会, 東京, 日本
13. Kayoko Miyazaki, Katsuhiko Miyazaki, Kenji Doya (2023). SEROTONIN NEURONS IN THE DORSAL RAPHE NUCLEUS ENCODE PROBABILITY RATHER THAN VALUE OF FUTURE REWARDS, 11th IBRO World Congress of Neuroscience, Granada, Spain
14. Jianning Chen (2023). Neurocomputational investigation of human schema-based learning, decision making and their modulators in ecological settings, SfN 2023, Washington D.C, US
15. Yuma Kajihara, Paulette Garcia-Andaluz, Katsuhiko Miyazaki, Hiroto Ashitomi, Kazumasa Z. Tanaka, Kenji Doya(2023). The role of serotonergic input to the paraventricular thalamus in reinforcement learning, SfN 2023, Washington D.C, US
16. Yukako Yamane, Yuzhe Li, Carlos Enrique Gutierrez, Takayuki Hashimoto, Keita Matsumoto, Shogo Akiyama, Rei Hashimoto, Kenichi Ohki, Kenji Doya (2023). Introduction of optical imaging data analysis tool, OptiNiSt, Mechanism of Brain and Mind Winter Workshop 2024, Hokkaido, JAPAN
17. Sutashu Tomonaga, Haruo Mizutani, Kenji Doya (2023). A novel approach to capturing multi-time scale dynamics in wearable device data using latent variable modeling, Mechanism of Brain and Mind Winter Workshop 2024, Hokkaido, JAPAN

18. Naohiro Yamauchi (2023). Multilayer imaging of the mouse motor cortex and modeling by reinforcement learning, Mechanism of Brain and Mind Winter Workshop 2024, Hokkaido, JAPAN
19. Miles Desforges (2023). In the motor cortex, serotonin, noradrenaline and dopamine dynamics align more with locomotion than reward or punishment. Mechanism of Brain and Mind Winter Workshop 2024, Hokkaido, JAPAN
20. Terezie Sedlinska (2023). Thrifty Hyper-Altruism and Impulsivity in Major Depression, Mechanism of Brain and Mind Winter Workshop 2024, Hokkaido, JAPAN
21. 町田 樹，山根 ゆか子，酒井 宏(2023). サル視覚野 V4 における形状の同時符号化，日本視覚学会 2024 冬季大会，東京都,日本
22. Lalande F (2023). A Transformer Model for Symbolic Regression towards Scientific Discovery, Nobel Turing Challenge Initiative Workshop, Tokyo, JAPAN
23. Naohiro Yamauchi (2023). Action value representation in the mouse primary motor cortex, Sensorimotor circuits for limb control, OIST
24. Sutashu Tomonaga, Haruo Mizutani, Kenji Doya (2023). A Novel Approach to Capturing Multi-Time Scale Dynamics in Wearable Device Data using Latent Variable Modeling, Machine Learning Summer School (MLSS 2024), OIST
25. Lalande F (2023). A Transformer Model for Symbolic Regression towards Scientific Discovery, Machine Learning Summer School (MLSS 2024), OIST
26. Tojoarisoa Rakotoaritina (2023). Embodied Evolution of Intrinsically Motivated Reinforcement Learning, Neural Computation Workshop 2024, OIST
27. Shuhei Hara, Keita Suzuki, Akio Murakami, Kei Majima, Mohamed Abdelhack, Fan Cheng, Hidehiko Takahashi, Kenji Doya (2023). Elucidation of the dysfunction in sensory processing in schizophrenia, CPSY TOKYO 2024, Tokyo, JAPAN
28. Sutashu Tomonaga, Haruo Mizutani, Kenji Doya (2023). A Novel Approach to Capturing Multi-Time Scale Dynamics in Wearable Device Data using Latent Variable Modeling, CPSY TOKYO 2024, Tokyo, JAPAN
29. Kayoko Miyazaki (2023). Serotonin - the neural mechanisms of optimism and pessimism, The 101st Annual Meeting of The Physiological Society of Japan, Fukuoka, Japan

5. Intellectual Property Rights and Other Specific Achievements

Nothing to report

6. Meetings and Events

([NOTE] You can include the following in "6. Meetings and Events":
(1) Seminars and workshops by guest speaker(s)
(2) Seminars and workshops by guest speaker(s) and OIST faculty member(s)/unit member(s)

6.1 Workshops and other events

Vision Science Forum 2023

- Date: October 26, 2023 - 16:00 to Friday, October 27, 2023 - 17:00

- Venue: OIST Conference Center
- Co-organizers: Vision Science Forum,
- Speakers:
    - Yu Takagi (National Institute of Informatics)
    - Yuko Yotsumoto (The University of Tokyo)
    - Hiroaki Gomi (NTT)
    - Kowa Koida (Toyohashi University of Technology)
    - Sam Reiter (Okinawa Institute of Science and Technology)
    - Masataka Sawayama (The University of Tokyo)
    - Tomonari Murakami (The University of Tokyo)
    - Ko Sakai (University of Tsukuba)
    - Ichiro Masai (Okinawa Institute of Science and Technology)

The second research area meeting of Transformative Research Area (A) : Unified Theory of Prediction and Action

- Date: November 4, 2023
- Venue: OIST Conference Center
- URL: https://groups.oist.jp/ncu/event/second-research-area-meeting-transformative-research-area-%EF%BC%9Aunified-theory-prediction-and
- Sponsor: Kakenhi Project on Development and validation of a unified theory of prediction and action

The Machine Learning Summer School in Okinawa 2024

- Date: March 4 – March 15, 2024
- Venue: OIST Auditriam and Conference Center
- URL: https://groups.oist.jp/mlss
- Sponsors: OIST and RIKEN AIP

Neural Computation Workshop 2024 (FY2023)

- Date: March 16, 2024
- Venue: OIST Seaside House
- URL: https://groups.oist.jp/ncu/event/neural-computation-workshop-2023
- Sponsors: Neural Computation Unit

6.2 Seminars by Visitors

Successor features representations: Human-inspired transfer reinforcement learning and its application to social robotics

- Date: September 22, 2023
- Venue: OIST Campus Seminar room B503, Center Bldg
- Speaker: Dr. Chris Reinke (Inria Grenoble)

Dynamics and learning - Future of AI with robotics applications

- Date: December 11, 2023
- Venue: OIST Campus Meeting Room D015
- Speaker: Mr. Motoya Ohnishi (The Paul G. Allen School of CS & E, University of Washington)

A recurrence-based direct method for stability analysis

- Date: December 25, 2023
- Venue: OIST Campus Meeting Room D015
- Speaker: Mr. Roy Siegelmann (the Mallada Laboratory, Johns Hopkins Whiting School of Engineering)

Understanding and shaping implicit brain functions that support physical and mental skills in sports

- Date: March 7, 2024
- Venue: OIST Campus Seminar Room C209, Ctr. Bldg
- Speaker: Dr. Makio KASHINO (Kashino Diverse Brain Research Laboratory, NTT Communication Science Laboratories)

7. Other

Nothing to report.