Moonshot Goal 1 Kanai Project

Internet of Brains (IoB)

What is Moonshot Goal 1 Kanai Project Internet of Brains (IoB) ?

PROJECT

Liberation from Biological Limitations via Physical, Cognitive and Perceptual Augmentation

Moonshot Goal 1 aims at the "Realization of a society in which human beings can be free from limitations of body, brain, space, and time by 2050" by developing technologies that can be applied to daily life and allow anyone to freely enhance their physical and cognitive abilities by utilizing Cybernetic Avatars (CAs), while also promoting these technologies within society.

Project Manager
Ryota KANAI, Ph.D.

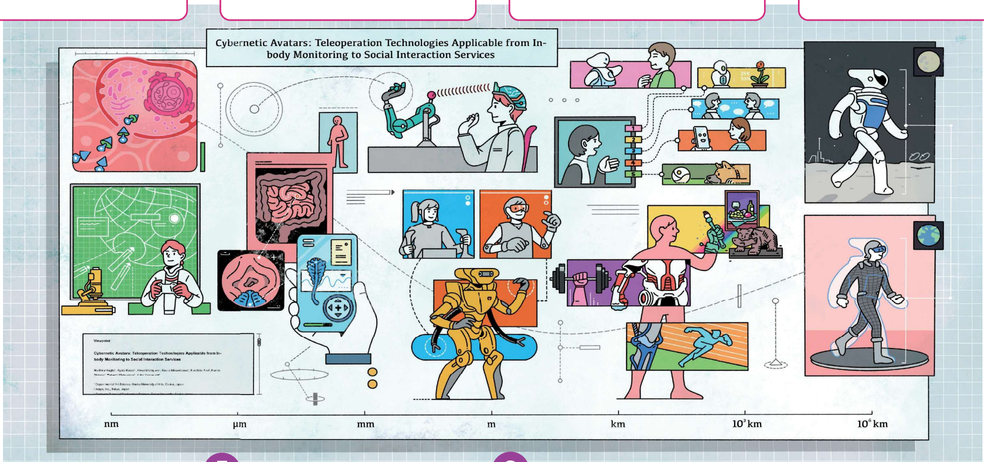
CEO, Araya Inc.
Director, Advanced Telecommunications Research Institute International (ATR)

A Teleoperating intracellular avatars from outside the body

B Operating a robotic arm with brainwaves

C Operating multiple robots or avatars by oneself

D Operating a robot from Earth to explore the Moon



E Monitoring gut health with in-body avatars

F Operating a single robot with multiple people

G Enhancing physical abilities with wearable devices

Q1 Which technology would you like to try?

Future conceptual illustration of Cybernetic Avatars (CAs) under Moonshot Goal 1

Outreach activities across various communication channels

Internet of Brains
IoB Official Website

Official X Account

Official YouTube Channel

A Communication Project with Society 「Neu World」

Neu World is a communication project led by the Internet of Brains (IoB).
While IoB is conducting cutting-edge research on the brain and AI to realize new ways of living, there exists a communication gap between research and daily life that cannot be bridged by research publications alone. To address this, we launched Neu World as a project that brings together writers, creators, researchers, and citizens to create sci-fi works. These works serve as a starting point for dialogues about the future, sparking actions that lead to the next steps.

Neu world

「Neu World」
Official Website

Internet of Brains

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IoB Interface

Moonshot Research and Development Program Goal 1 Kanai Project

Non-Invasive BMI for Estimating Mental and Physical State

Junichi Ushiba, Faculty of Science and Technology, Keio University

Overview

The IoB Interface aims to popularize Brain-Machine Interface (BMI) technology by developing techniques to extract thoughts and mental states from brain activity using various devices and implementing them in society as applications. Specifically, we are developing algorithms that can quickly extract thoughts and mental states in daily environments by combining gadget-type EEG sensors, like headphones, with mobile phone camera images, among other data. By using these, we aim to proliferate BMI technology in society by creating applications that enable self-regulation through the visualization of daily physical changes that are not consciously recognized, and applications that support communication for users whose intentions cannot be externally expressed due to their condition or situation. The Ushiba Group, in particular, is promoting the creation of 'daily life with BMI' by developing small, wireless, and quickly attachable EEG sensors, along with AI filters that automatically separate the diverse noise encountered in real-world environments.

Compact, Wireless, and Quick-to-Apply EEG Sensor

Easy, Accurate EEG: Anytime, Anywhere

We all face moments when our mind and body don't move as intended, despite our best efforts — functional impairment of the mental or nervous system due to life events like aging, accidents, or injuries can happen to anyone. The wearable EEG sensor we are developing aims to visualize these mental and neurological issues and enable self-regulation.

Our proprietary device housing is meticulously engineered to allow anyone to easily and medically accurately record brainwaves, much like wearing a pair of headphones. The product features a stylish design that blends seamlessly into the urban environment. It incorporates ground and reference electrodes that naturally fit behind the ear and on the cheek. A length-adjustable headband ensures the electrodes are precisely positioned over the 'Central Region'—the critical brain area governing motor skills, sensation, cognition, and arousal. Furthermore, by integrating a spring mechanism in the electrode holders and utilizing a specialized sponge and proprietary lotion, we have achieved a skin-electrode impedance of less than 30 kΩ in just 30 seconds for any user.

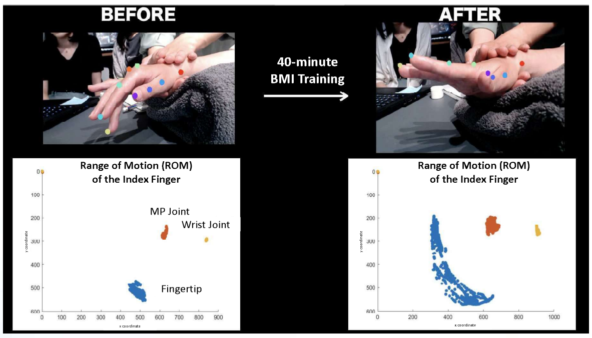
We believe this innovative technology will significantly accelerate the widespread public adoption of scientifically validated, wearable Brain-Computer Interfaces (BCIs).

Self-Care for the Brain

Some individuals, even after suffering a stroke and completing medical treatment to return to society, continue to struggle with fixed, persistent paralysis. By combining our newly developed EEG sensor with AI embedded in a tablet PC, we can visualize the activity of the neural circuits when the user attempts to move in real-time. Through training to self-regulate this activity, users can learn how to apply and release muscle tension, leading to a significant improvement in the range of motion of their fingers and hands.

Previously, it was difficult to directly capture the state of the "brain," which acts as the body's controller. However, with this EEG sensor, it will now be possible to directly visualize the motor signals emanating from the brain and use them for training.

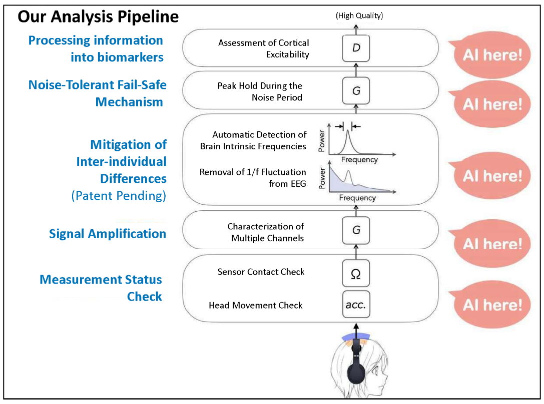
We are currently promoting efforts to expand the application of this technology not only to stroke rehabilitation but also to other diseases such as Dystonia and Parkinson's disease.



EEG Sensor Training for Motor Signal Output in Chronic Stroke Patients.

Protecting Brain Signals from Noise with AI

As brainwaves are extremely faint signals, measured in just a few microvolts, they are susceptible to diverse noise contamination for various reasons. We have made a science of this "noise," developing a technology that applies AI to each noise component for fully automated signal cleansing. We utilize an AI engine capable of analyzing scalp EEG with physiological quality, even in real-world environments.



Signal Quality Assurance via ML/Statistical Modeling Optimized per Noise Process.

Race Your Avatar with Your Brainwaves!

To verify the performance of our developed EEG sensor and AI technology, we offered over 2,200 visitors a "brainwave-controlled avatar" game experience over 10 days at the Osaka-Kansai Expo. The technical success of achieving one-touch, 30-second EEG measurement for every single participant was significant. More importantly, this futuristic experience of controlling an avatar with brainwaves helped widely demonstrate the contribution of BMI technology to realizing a society where everyone can connect, regardless of disability.

Highlights of the 10-Day BCI Brainpic Experience Exhibition (Starting Aug. 20, 2025)

Future Prospects

We aim to realize a future society where individuals facing difficulties in daily life due to brain or physical constraints can be supported by AI-driven BMI (Brain-Machine Interface) technology and avatar control technology. To this end, following appropriate review and approval processes, we will proceed with the intellectual property transfer to LIFESCAPES Co., Ltd.—the BMI manufacturer I founded and concurrently serve at—and other partner companies, to promote sustainable commercialization both domestically and internationally. Through these efforts, we will deepen the science of the brain and AI, and cultivate the next generation of talent knowledgeable in the harmonization of science and business.

Junichi Ushiba

Professor, Faculty of Science and Technology, Keio University

Born July 8, 1978, in Tokyo. Graduated from the Faculty of Science and Technology, Keio University, in 2001. Obtained a Ph.D. in Engineering in 2004. In the same year, appointed as Assistant in the Department of Biosciences and Informatics. Subsequently served as Lecturer (from '07), Associate Professor (from '12), and Principal Investigator at the Institute of Basic Science and Fundamental Engineering (from '14 to '18), before becoming a Professor in 2022. Concurrently serves as President and Representative Director of LIFESCAPES Inc., a venture company utilizing research outcomes (since '19). Accolades include being a Top 10-12 Nominee for The BCI Research Award in 2024, 2019, 2017, 2013, 2012, and 2010, and receiving The Young Scientists' Prize from the Ministry of Education, Culture, Sports, Science and Technology (FY2015, for research on Neural Medicine using Brain-Machine Interface), among others.

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Non-Invasive BMI for Mental and Physical State Regulation

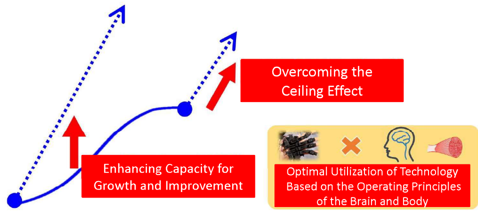
Shinichi Furuya, Research Director of Tokyo Research, Sony Computer Science Laboratories, Inc.,

Moonshot Research and Development Program Goal 1 Kanai Project

IoB Interface

Overview

What determines the limits of our abilities? Naturally, a significant portion is determined by innate genetics. However, the factors that define the limitations we feel during daily life or advanced training have not been fully elucidated until now.
Our project has been dedicated to developing non-invasive brain function assessment technologies and training systems based on robotics and neuroscience, aiming to break through the limits of the brain, mind, and body, and realize a future society where everyone can enjoy the joy of manifesting creativity. By gaining a deeper understanding of our own brain and body, we have discovered that the abilities we once believed to be "limits" still possess room for growth, or "potential," that can be improved through the right methods.



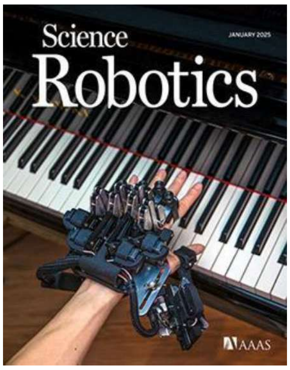
Breaking Through the Limits of Brain, Body, and Mind Through the Fusion of Science and Technology

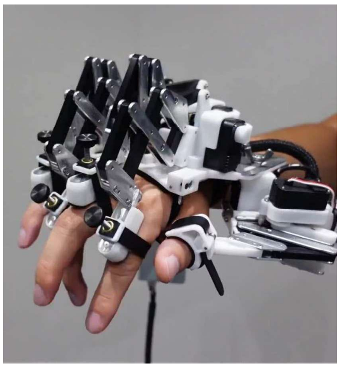
Brain Encoding Technology to Break Through Skill Limits

For experts—including pianists, athletes, and surgeons—who have practiced for many years, the "ceiling effect," where skill improvement stagnates at a certain point, becomes a major issue. Traditionally, attempts have been made to break through this by increasing practice volume, but excessive practice carries the risk of injury and failure, and its effectiveness has often been reported as insufficient. Furthermore, high-speed and complex movements are often impossible to experience firsthand, posing a challenge where skills are difficult to acquire through verbal instruction alone.

- Approximately 100 expert pianists experienced complex and high-speed finger movements—which were impossible for them to perform on their own—by wearing an exoskeleton robot capable of independently moving their fingers at high speed.
- The training involved two weeks of regular practice at home to establish a plateau in their skill level, followed by training using the exoskeleton robot.
- Training while wearing the robot enabled participants to play complex and high-speed musical pieces faster than their previous limit while maintaining accuracy.
- The effect was observed not only in the trained hand but also in the opposite hand.
- While no changes were observed in finger strength, agility, or sensory functions, plasticity (functional changes in the brain) was confirmed in the motor cortex (cerebral cortex).
- This suggests that the passive experience "wrote" the skill of high-speed, complex movements into the motor cortex of the brain.

This research presents the idea that the "ceiling effect" is not an unchangeable limit, and that this limit can be overcome with high-quality experience. Applications are anticipated not only in music but also in improving skills in sports and surgical procedures, and even in preventing injuries caused by over-practice. In the future, this technology is expected to lead to the widespread adoption of new training programs utilizing such exoskeleton robots and Virtual Reality (VR) technology, and the development of education and skill acquisition methods that transcend the constraints of human creativity and physical ability.





The results were featured on the cover of *Science Robotics* and by *The Times*, *BBC News*, and so on.

Technology for Estimating Brain State

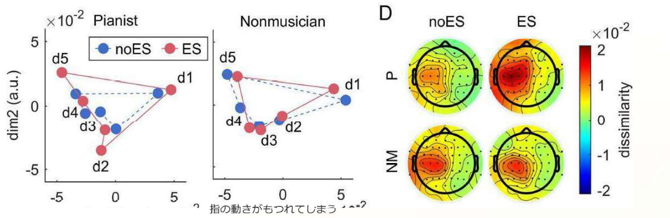
Brain condition varies from day to day. Using a headphone-type EEG device developed by the Ushiba SPM group, we continuously measured the preparatory brain waves of junior pianists in our Piano Academy over a long period of one year.

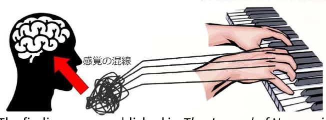
By extracting and analyzing a component known as 1/f fluctuation (or 1/f noise) from the EEG signals, we successfully predicted the day-to-day differences in their performance. This suggests the possibility of estimating a person's subconscious state of wellness or decline using non-invasive brain function measurement combined with data science technology.

Academy student with international competition awards

Technology for Conditioning Brain State

Feeling that one's "body is out of condition" is a critical problem for professionals whose careers rely on physical movement, such as athletes, musicians, and surgeons. In particular, when executing delicate movements, fumbled finger movements leading to failure can sometimes compromise the quality of medical care, culture, or industry. Behind this issue, we discovered a mechanism where force and tactile information sent from each finger is not correctly routed to the respective "finger rooms" within the brain. Furthermore, we found that applying imperceptible, weak electrical stimulation to the peripheral nerves is an effective brain conditioning technique to prevent information from different fingers from becoming confused or crosstalking in the brain.





(Left) Mechanism of sensory crosstalk in the brain, causing tangled finger movements. (Upper) Discovery in experts: Peripheral electrical stimulation increases the distance between the brain's "finger rooms."

The findings were published in *The Journal of Neuroscience.*

Future Prospects

The ability to predict a person's condition from their brain state suggests the possibility of achieving "Peaking"—the regulation of the brain's state using BMI technology. We have developed a prototype system for this purpose. Moving forward, we aim to verify its effectiveness and realize a world where it is possible to optimize one's brain state.

Furthermore, it has become clear that what we once believed to be the limits of our body and mind can be broken through by science and technology. We are working on expanding one such means—the exoskeleton robot—to the entire body, to enable breakthroughs in the limits of more advanced and complex skills, and to realize technology that can transfer tacit knowledge cultivated over many years to others, and ensure its continuous inheritance across generations.

Just as sports science and National Training Centers exist for athletes, we will also strive to establish the science and training centers for performing artists, aiming for the sustainable development of culture.

Shinichi Furuya

Research Director, Tokyo Research, Sony Computer Science Laboratories, Inc.

Research Director, Tokyo Research, Sony Computer Science Laboratories, Inc.; Representative Director, NeuroPiano (General Incorporated Association); Visiting Professor, Hanover University of Music, Drama and Media; Part-time Lecturer at Tokyo University of the Arts, Kyoto City University of Arts, and Toho Gakuen School of Music; Specially Appointed Professor, Tokyo College of Music. After studying at the Faculty of Engineering Science and the Graduate School of Human Sciences, Osaka University, obtained a Ph.D. in Medicine from the Graduate School of Medicine. Previously held positions at the Department of Neuroscience, University of Minnesota; the Institute for Music Physiology and Musicians' Medicine, Hanover University of Music, Drama and Media; and the Faculty of Science and Technology, Sophia University, before assuming current roles. Major research awards include the DFG (German Research Foundation) Heisenberg Fellowship, the Klein Vogelbach Prize, the Alexander von Humboldt Foundation Postdoctoral Fellowship, the MEXT (Ministry of Education, Culture, Sports, Science and Technology) Leading Initiative for Excellent Young Researchers, and the Japan Society for the Promotion of Science (JSPS) Prize, among others. Major performance activities include performing at the Ernest Bloch Music Festival (USA) and winning an award at the KOBE International Music Competition, etc. Major publications and translations include The Science of the Pianist's Brain and What Every Pianist Should Know About the Body.

Project Members
Masato Hirano／Pei-Cheng Shih／Hayato Nishioka／Yuki Ogasawara／Sachiko Shiotani／Momoko Shioki

Internet of Brains

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IoB Interface

Moonshot Research and Development Program Goal 1 Kanai Project

Mood Estimation from Non-Contact Information

Ai Koizumi, Researcher, Sony Computer Science Laboratories, Inc.

Overview

This research and development project, conducted under the JST Moonshot Goal "Liberation from the constraints of body, space, and time through expansion of physical and perceptual capabilities" (PM: Kanai), is advancing foundational technology for estimating mood and psycho-physical states from non-contact physiological information, alongside demonstrations for social implementation. We measure heart rate, sweating, pupil dilation, eye movements, facial expressions, and body sway, among other factors, using wearables and smartphones in both laboratory and daily life settings. AI is then used to estimate the current state and predict the near future, which is translated into concrete feedback for schedule adjustments and self-care.

We particularly focus on high-risk populations who may lack access to support, such as those requiring PTSD prevention after accidents. In collaboration with medical and welfare institutions, we will also test the provision of safe communities utilizing anonymous avatars and cognitive behavioral training in virtual spaces. Our ultimate goal is to realize a society where everyone can benefit from BMI (Brain-Machine Interface) in their daily lives, without dependence on specialized experimental equipment or skilled experts.

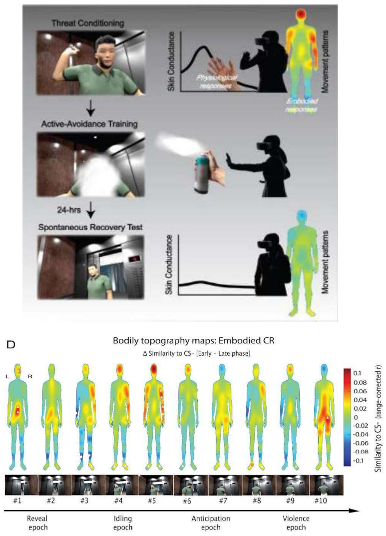
Estimating Individual and Collective Mood from Body Movement

We are developing technology to subtly interpret mental states based solely on body movement. First, we analyzed behavior and physiological reactions in a VR environment to extract movement patterns that reflect fear and tension. We demonstrated that when participants practiced avoidance maneuvers using their own gestures in a 3D VR space after fear conditioning, physiological indices (such as galvanic skin response) and movement indices remained significantly reduced even on the following day (24 hours later) (iScience 2024). The characteristic finding is that training through active body movement showed greater persistence of effect compared to observation only or conventional "fear extinction" methods. This research is also considering a prototype application that allows users to practice avoidance maneuvers using their smartphone as a controller (the effectiveness of which is yet to be verified). Through these attempts, we aim to eventually be able to monitor signs of individual mental distress using non-contact technology with anonymity safeguards, without disrupting daily activities.

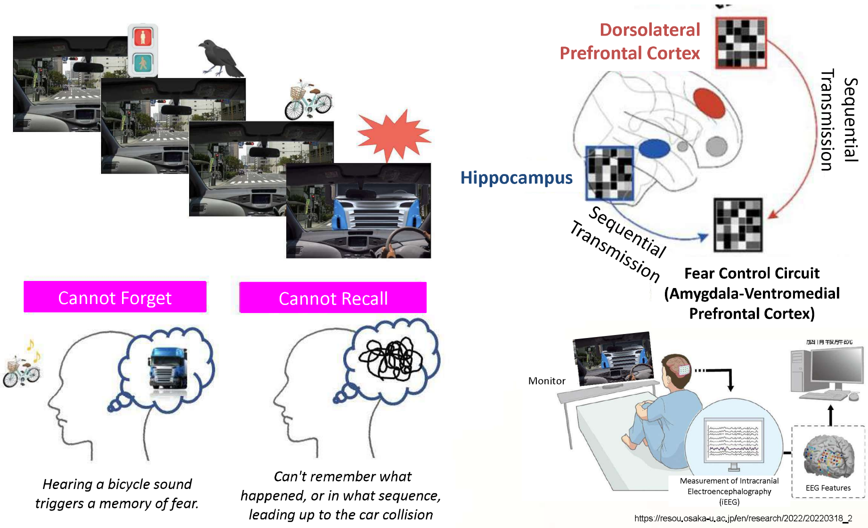
Tracing the Dynamics of Fear Memory Through Body and Brain

Fearful experiences can create a paradoxical phenomenon: simultaneously being "unforgettable" and "unrecallable." We demonstrated that on the day of a fearful experience, the scope of fear broadens due to associative memory, but on subsequent days, the scope narrows as the temporal sequence of the experience is consolidated. This day-to-day change can be explained by a shift in the balance of how the hippocampus and dorsolateral prefrontal cortex transmit temporal sequence information to the amygdala–ventromedial prefrontal cortex circuit.

Furthermore, this switching mechanism is weaker in individuals with anxiety traits, who are at higher risk for PTSD. The reduced encoding of temporal sequence information may contribute to the symptoms of being "unforgettable (associative)" yet "unrecallable (sequential)." These findings were reported in *Nature Communications* (2024). To transition these results into real-world implementation in line with the Moonshot goal, we are currently conducting detailed verification using intracranial recordings in collaboration with Yanagisawa SPM.



Extraction of Fear and Tension from Movement Patterns (iScience 2024)



Research findings using fMRI (Nature Comm 2024) and verification content using intracranial recordings (Ongoing)

Future Prospects

We will begin with small-scale pilot programs in schools and workplaces to test a system that "gently monitors" individuals using **non-contact technology while prioritizing anonymity**. This system visualizes mood fluctuations and connects them to simple feedback, such as **suggestions for breaks or basic breathing and avoidance training**. Collaborating with experts in medicine, welfare, and design, and while rigorously verifying **fairness and explainability**, we will expand this to **areas in need of support**, such as PTSD prevention and women's mental health. Through these efforts, we will steadily advance the implementation of a "daily life with BMI (Brain-Machine Interface)."

Ai Koizumi

Researcher

Graduated from the State University of New York (double major in Psychology and Film Studies), and obtained a Ph.D. in Psychology from the Graduate School of Humanities and Sociology, The University of Tokyo. After serving as a Postdoctoral Researcher at the Department of Psychology, Columbia University, and as a Researcher at the Center for Information and Neural Networks (CiNet), National Institute of Information and Communications Technology (NICT), became a Researcher at Sony Computer Science Laboratories, Inc. in January 2019. Currently serves as a Collaborative Researcher at the Advanced Telecommunications Research Institute International (ATR) and as a PRESTO Researcher at the Japan Science and Technology Agency (JST).

Maria Alemany Gonzalez

Postdoctoral Researcher

Amirmahmoud Houshmand Chatroudi

Postdoctoral Researcher

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IoB Interface

Moonshot Research and Development Program Goal 1 Kanai Project

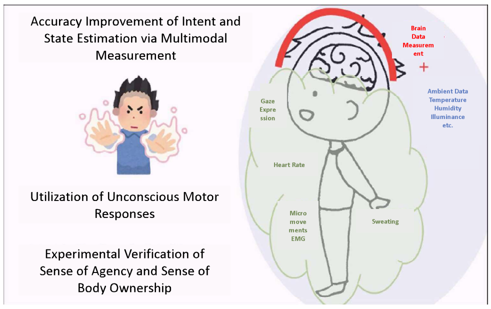
Human-Centered BMI

—Harnessing Users' Conscious and Unconscious Processes—

Katsumi Watanabe, Professor, Faculty of Science and Engineering, Waseda University

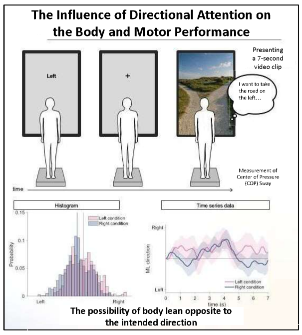
Overview

This research aims to accumulate scientific knowledge regarding the estimation of psycho-physical states applicable to BMI (Brain-Machine Interface) and Cybernetic Avatar (CA) related technologies, and to conduct R&D on utilizing latent information appearing on the body surface. Specifically, we will clarify the limits and scope of intentions and mental states decodable from non-contact surface information, and seek to improve performance and expand applicability in daily life by combining this information complementarily with brain information. Furthermore, anticipating a future with multiple operators and multiple CAs, we will conduct research to elucidate the relationships between sense of body ownership, sense of agency, and performance. This will establish a scientific foundation for measuring and improving the user experience of BMI technology and CAs for both individuals and groups.

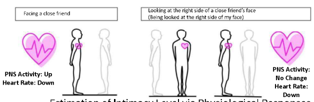


R&D Approach: Utilizing Involuntary Responses and Their Underlying Processes

Harnessing Unconscious Body and Behavioral Reactions



Unconscious Center of Gravity Shift



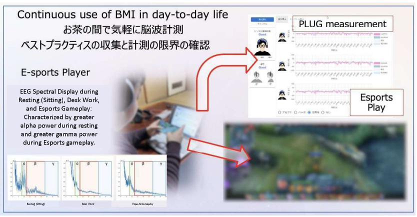
Estimation of Intimacy Level via Physiological Responses

Even when people believe they are doing nothing (or actively trying to be still), their intentions, emotions, and other internal states manifest in their face, body, and behavior. In this research theme, we do not treat such unconscious reactions as mere noise. Instead, we regard them as crucial information that complements BMI technology designed to liberate humans, and we are accumulating scientific knowledge that will lead to technologies realizing a state of greater control and freedom.

For example, findings such as "unconscious shifts of body weight to the right when intending to move left," "changes in body weight distribution when a face of someone who committed a moral wrong is presented," and "changes in heart rate and parasympathetic nerve activity depending on whether a close friend is directly in front or to the right" are all pieces of information unknowingly broadcast by humans. By combining these with BMI data, we expect to improve the accuracy of intention and state estimation.

BMI in Daily Life

For new technologies, including BMI, to permeate society, not only technological advances but also how they are used in daily life and how they are accepted by society are crucial. Based on the perspective that "there are things we only discover through actual use," this project aims to continuously measure data over a long period. Rather than giving up on the challenge of measurement in daily life as too difficult, we are proceeding to discover, in a bottom-up manner, "when measurement is truly possible" and "what usage patterns lead to greater utility".



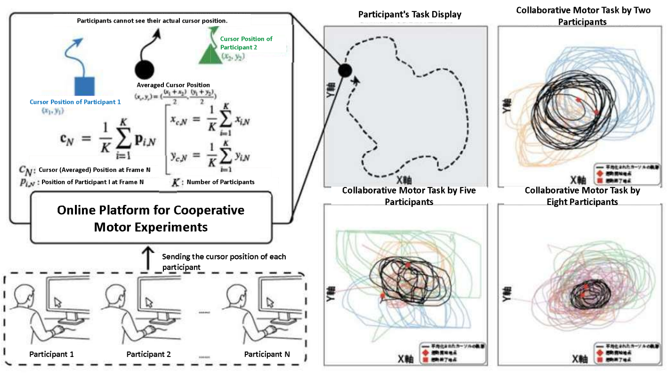
EEG While Playing Online Games in the Living Room

Building the Research Foundation for Agency Engineering

One of the key concepts of Goal 1 is the Cybernetic Avatar (CA). CAs are entities that operate as extensions of oneself, whether in the physical or virtual world. The future we envision includes scenarios where "multiple operators control a single CA," "one operator controls multiple CAs," and even "multiple operators control multiple CAs." While goals include enhancing productivity and creativity, for these technologies to truly lead to human joy and value, maintaining and improving the user's sense of "being the agent" (sense of agency) and sense of "being a participant" (sense of contribution) are essential.

In cognitive science and neuroscience, a significant body of research has been accumulated on individual sense of agency, but very little research has explored multiple operators or multiple CAs. Therefore, we are conducting cross-team R&D to investigate the relationships among sense of body ownership, sense of agency, and performance, assuming a future where multiple operators and multiple CAs exist.

For instance, consider a task where a large group of people tries to draw a circle as smoothly as possible using a single cursor. Individual participants can only see the average position of the cursor from all inputs. By meticulously analyzing aspects such as "how task performance changes," "whether the team succeeded," "how much one contributed," and "whether one can respond cooperatively to others' inputs" in such a situation, we aim to clarify the characteristics, limitations, and expandability of multi-CA operation and multi-subject participation. Specifically, we are exploring methods to optimize the actual contribution of each individual while maintaining the multiple operators' sense of agency and subjective contribution. Furthermore, this knowledge may provide guidelines on when and to what extent AI support should be introduced into CA operation and BMI technology.



Developing an Experimental Platform for Group Collaboration

Future Prospects

When aiming to enhance productivity and creativity while simultaneously maintaining (or improving) individual well-being, we believe that understanding the "conscious and unconscious processes of the user (human)" is crucial. This is just as important as technological progress in clarifying how to measure the "subjective experience" of users employing CA and BMI technologies, and how that information should be fed back to society and individuals. Moving forward, we will continue to conduct research that prioritizes the "feelings" (mental states) of both individuals and groups, anticipating the future to be achieved through the Moonshot program.

Katsumi Watanabe

Professor, Faculty of Science and Engineering, Waseda University

Completed the Computational and Neural Systems program at California Institute of Technology (Caltech) in 2001 (PhD). At the current position after serving as Associate Professor at the Research Center for Advanced Science and Technology, The University of Tokyo, and other roles. Has participated in the Moonshot program since 2020. Specializes in Cognitive Science, Psychology (Cognitive Psychology), and Neuroscience. Conducts research aimed at the scientific elucidation of the conscious and unconscious processes that create the subjective phenomenon of the human mind, using cutting-edge methods from cognitive science, psychology, and neuroscience; the expansion of cognitive science to other research fields; and the societal implementation of these findings through industry-academia collaboration.

Shunichi Kasahara

Researcher, Sony Computer Science Laboratories, Inc.

Kazuma Takada

Ph.D. student, Embodeid Cognitive Science unit, Okinawa Institute of Science and Technology Graduate University

Kae Mukai

Assistant professor, School of Informatics, Nagoya University

Risako Shirai

Researcher, Faculty of Science and Engineering, Waseda University

We also receive support from numerous other contributors.

Internet of Brains

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IoB Middleware

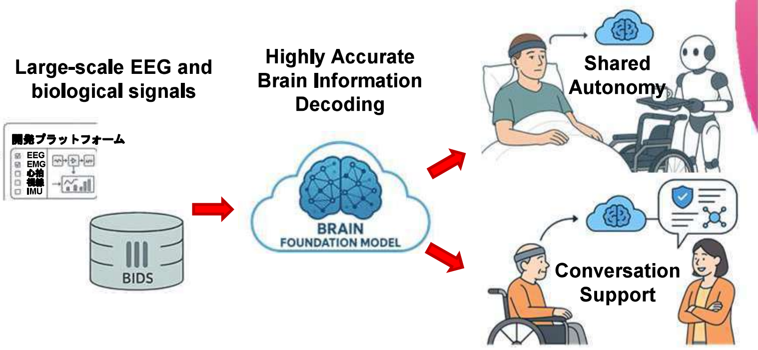
Moonshot Research and Development Program Goal 1 Kanai Project

X Communication

CRO & Head of R&D Department, Araya inc. / Moonshot Goal 1 Kanai Project SPM
Shuntaro Sasai, Ph.D.

Overview

By collecting large-scale EEG and biological signals without invasive surgery, we aim to develop AI that accurately predicts users' "intentions" and create systems that autonomously support daily living. This technology seeks to build a society where everyone, including those who find physical operation difficult, can live free from limitations.



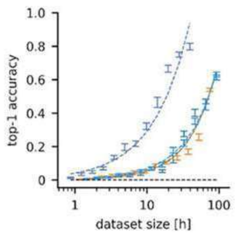
Discovery of Scaling Laws in Speech Decoding Using EEG

Electroencephalography (EEG) is a representative non-invasive measurement technique. Its potential for wearable implementation has led to its widespread use in research as a sensing device for Brain-Machine Interfaces (BMIs). However, because EEG signals are measured from the scalp, they contain various noise from body movements and the surrounding environment. Consequently, practical applications for decoding highly complex brain information, such as speech, have been considered difficult.

Recently, it has been shown that the accuracy of AI systems, such as Large Language Models (LLMs), follows an empirical rule known as the scaling law, where performance improves with the amount of data used for training. However, it was unknown whether this scaling law applied similarly to EEG decoding. To address this question, the X Communication team (Araya Inc.) trained an AI using over 400 hours of EEG data recorded from the same subject while reading aloud. They successfully achieved 60-80% accuracy in correctly identifying 512 speech segments from the EEG data.

High-Density EEG | Dense array EEG

Decoding accuracy improves with training data

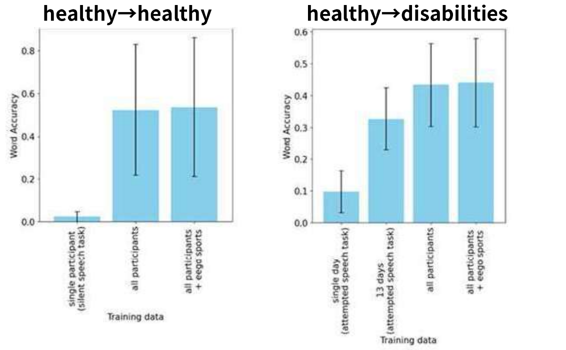


Building a Scaling-Law-Driven EEG Data Infrastructure
～Improving Speech Decoding Accuracy for Individuals with Disabilities Using EEG Data from Others～

The discovery of scaling laws suggests that accumulating large-scale data enables highly accurate and flexible brain information decoding using EEG. However, EEG data exhibits significant variability between subjects, and it was unclear whether a model trained on EEG data from one cohort could generalize to other individuals. This study, however, demonstrates that only a small amount of data from a target individual, supplementing it with EEG data from other people can improve speech decoding accuracy. Moreover, this improvement is observed not only among healthy individuals but also between healthy subjects and patients with severe neurological disorders who are largely unable to speak or move. This suggests that building a large-scale EEG data platform could greatly reduce the initial burden of adopting BMI technologies.

Improving accuracy using other subjects' data

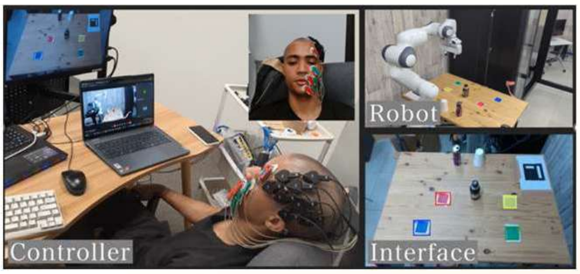
healthy→healthy | healthy→disabilities



※Results of measurement using the cEEGrid (16 electrodes around the ear), a simple device designed for daily use.

Remote Control of a Robotic Arm Using High-Density EEG

The X Communication Team and Reinforcement Learning Team (Araya Inc.) have successfully operated a robotic arm remotely using ultra-high-density EEG and AI. In this study, we trained AI to predict spoken color names from EEG signals and to guide the robotic arm to target points corresponding to the predicted colors.. Additionally, imitation learning was employed to achieve remote operation of the robotic arm.



Future Prospects

Currently, achieving high-accuracy speech decoding requires speech-like movements (even without vocalization), similar to lip-syncing. Furthermore, it remains unclear whether decoding is possible in environments involving significant body movement or high ambient noise. Moving forward, we will focus on developing middleware technology that enables stable decoding without the need for speech movements, even in environments with significant body movement or high ambient noise.

Shuntaro Sasai, Ph.D

CRO & Head of R&D Department, Araya inc. / Moonshot Goal 1 Kanai Project SPM

He received his Ph.D. from the Graduate School of Education at the University of Tokyo in 2013 (accelerated completion). He subsequently moved to the United States and joined the University of Wisconsin–Madison School of Medicine as a research fellow, where he investigated the neural mechanisms of consciousness. Working closely with the proponent of the Integrated Information Theory (IIT) of consciousness, he contributed both to the refinement of the theoretical framework and to its empirical validation. His work led to the identification of brain regions corresponding to the neural substrates of consciousness. After returning to Japan, he joined Araya, Inc. in November 2020 and has held his current position since October 2021. He is currently engaged in foundational research at the intersection of neuroscience and artificial intelligence, as well as in the development of novel neurotechnology products that apply consciousness theory toward the societal implementation of "mind-connecting" brain–machine interfaces (BMIs).

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Internet of Brains

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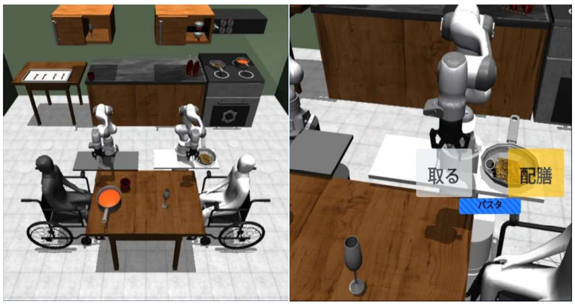
Brainwave–Controlled Assistive Robot

Dr. Kai Arulkumaran

Overview

The Reinforcement Learning Team at Araya Inc. conducts research on assistive robotics, brain–robot interfaces, and multi-agent systems. As part of a Moonshot research initiative, the team envisions future societal technologies and advances the development of assistive robots that support individuals with motor impairments and senior citizen. This work integrates neural signal acquisition and decoding, control theory, reinforcement learning, and multi-agent algorithms.
The team's objective is not merely to provide assistance, but to enable users to maintain a sense of autonomy, engage in social interaction, and ultimately contribute to society. To achieve this, the team pursues interdisciplinary research at the intersection of machine learning, robotics, neuroscience, and human–computer interaction (HCI).

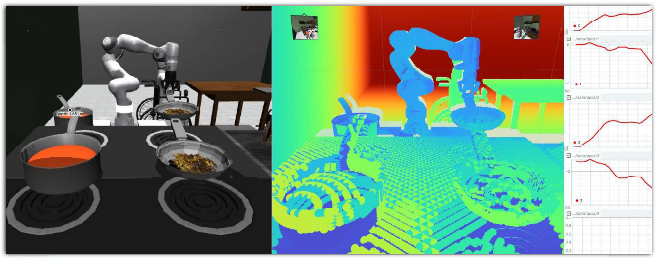
Kitchen Work Assistance Robot System



To develop a robotic system capable of assisting with kitchen-related tasks, we are constructing a virtual kitchen environment referred to as the "Assistive Kitchen Environment." In this scenario, two users—each assumed to have physical disabilities—are paired with an individual mobile robotic arm. The users' task is to collaboratively set the dining table by operating their respective robots using EEG-based neural signals and an eye-tracking interface. Specifically, users designate target locations or objects (e.g., dishes to pick up, items to place on the table) through their gaze. Additionally, users may be asked to imagine specific actions they wish the robot to perform (such as serving a meal), enabling intent decoding via machine learning algorithms applied to real-time EEG signals.

Realizing this system requires the integration of several components: the construction of a robotics simulation environment, the design of a user-friendly interface, the development and training of AI models capable of real-time neural signal decoding, and the creation of software that coordinates all these elements. To maximize user autonomy, the system allows manipulation of various items such as cupboards, cups, glasses, and stovetops. Furthermore, to enable the robot to perform a diverse range of tasks instructed by the user, we integrate state-of-the-art techniques from computer vision, machine learning, and robotics.

While experiments are currently conducted in a simulated environment, we are developing methodologies that can be applied to real-world robotic systems.



Future Prospects

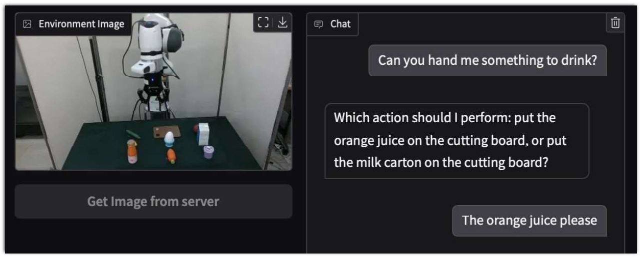
Our latest research outcome, the "Assistive Kitchen Environment," is currently under development within a simulation platform; however, we are actively pursuing technological advancements with real-world deployment in mind. Since the underlying AI and robotics algorithms are readily transferable to physical settings, our next step is to develop a mixed-reality (MR) interface that enables users to control a robot and manipulate objects directly within their surroundings. We aim to advance this line of research toward creating technologies that contribute to a more inclusive and supportive society.

Interdisciplinary approach

Advancing research and development in these domains requires a genuinely interdisciplinary approach. From a technical standpoint, it is essential to develop algorithms capable of efficiently analyzing human EEG and other physiological signals, as well as robotic control systems that offer versatility, efficiency, and safety, all while functioning in real time in real-world environments.

From a human-centered perspective, understanding users' needs and preferences is equally critical. For example, individuals with disabilities or older adults may require support in daily activities, yet they do not wish for assistance to be imposed upon them. In this study, we aim to balance technical requirements with users' expectations, with the overarching goal of empowering individuals to participate more actively in society.

Household robots



In this study, we also consider the introduction of robotic systems into home environments to assist daily activities such as household tasks. While the same algorithms for fine-grained robot control are employed, one of our objectives is to enable users to instruct the robot through natural language. Furthermore, by leveraging technologies derived from modern chatbot architectures, we envision a system in which users can issue commands through interactive dialogue using text or image-based inputs.

Beyond the conversational interface, these technologies support two additional key functionalities. First, they allow the robot to autonomously plan its actions in response to user instructions. For example, when given a command such as "clean the table," the robot's control algorithms decompose the task into a sequence of executable subtasks (e.g., "move to the table," "collect dirty dishes," "carry them to the kitchen"). Second, the system is designed to handle ambiguous instructions by prompting the user for clarification through dialogue. For instance, if a user asks the robot to bring a drink, the robot can query which specific beverage to retrieve when multiple options are available in the refrigerator.

Kai Arulkumaran
Visiting Researcher, Araya Inc.

Kai is a visiting researcher at Araya Inc. (formerly the leader of the Reinforcement Learning Team) and the Principal Investigator (PI) of the IoB Moonshot project. Prior to joining Araya Inc., he completed a B.A. in Computer Science at the University of Cambridge, followed by an M.Sc. and Ph.D. in Bioengineering at Imperial College London. During his doctoral studies, he gained research experience at Google DeepMind, Facebook AI Research, Twitter Cortex, and Microsoft Research.

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Decoding Neural Information Representation and Developing Middleware Technologies for IoB

Ryusuke Hayashi, Senior Researcher, Human Informatics and Interaction Research Institute, National Institute of Advanced Industrial Science and Technology (AIST)

Overview

In this project, we aim to create foundational IoB (Internet of Brains) technologies that enable individuals with severe physical and mental disabilities—such as profound impairments in speech and limb function—to achieve forms of communication and motor assistance that are otherwise extremely difficult without invasive neurophysiological recording. Our goal is to realize advanced communication capabilities through multimodal BMIs that integrate multiple modalities of intention decoding, as well as human-function augmentation through cognitive-agent (CA) operation.

As core technological components, we have developed novel AI architectures and mathematical frameworks—along with their experimental validation—toward achieving direct information exchange between brains, a concept we refer to as "X-Communication." Significant progress has been made in decoding neural information using large-scale datasets derived from spiking neural activity at the single-cell level, combined with multimodal and generative AI approaches.

In addition, we performed cross-species analyses of multimodal brain activity signals in nonhuman primates and humans. These efforts yielded advances in BMI technologies that enable the transmission of conceptual, sensory, affective, and material information between brains, as well as between the brain and AI systems.

Development of neurotechnology enabling communication of experiential qualities beyond the limits of language

- Convey not only **object category** but also **color**, **texture**, **shape**, and **material**.
- Convey **emotions** via **CA.**
- In the future, aim to develop foundational technologies for transmitting **aesthetic impressions, imagination, and other aspects of sensibility.**

Middleware development

- Development of **AI- and mathematical-based foundational technologies.**
- Construction of an **open-source neural database within MS**
- **PoF** of X-Communication through **animal experiments**

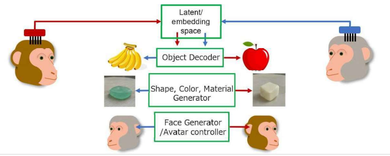


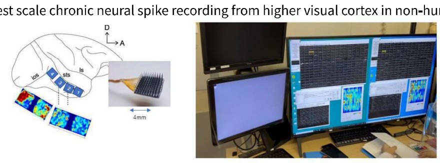
Image Reconstruction Technology Based on Neural Information from Higher-Order Visual Cortex

We have developed a large-scale neural recording system capable of simultaneously measuring single-neuron activity in nonhuman primates (macaque). To date, we have implanted chronic 512-channel electrode arrays into the higher-order visual cortex responsible for object recognition processing in two animals, enabling long-term, simultaneous recordings of electrical activity from several hundred to over one thousand neurons during awake behavior. This represents one of the largest chronic recording datasets ever achieved in higher-order visual areas worldwide. Using this system, we have recorded neural responses to tens of thousands of static images as well as neural activity during 27 hours of movie viewing, thereby establishing a foundational dataset for IoB technology development.

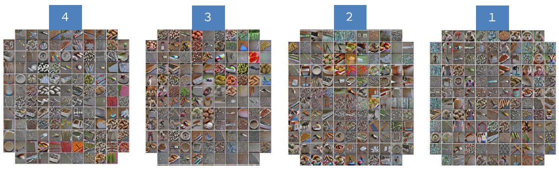
Leveraging the multimodal foundation model CLIP—which learns shared representations across images and language—we developed an information-processing architecture capable of bidirectional information transformation between brain activity and AI embeddings through supervised learning (learning with explicit correspondences between neural representations of brain and AI). By integrating this architecture into an image-generation model, we achieved high-fidelity reconstruction of images viewed by the animals based solely on ~500 ms of neural activity. The reconstructed images faithfully reproduce color, texture, shape, and object category.

Furthermore, by resolving correspondences between the neural signals obtained from individual electrodes and the representational space of the AI model, we successfully visualized functional maps of the cortex with spatial resolution determined by the electrode spacing (400 μm) and high temporal resolution (1 ms), thus enabling fine-grained mapping of cortical functional organization.

World's largest scale chronic neural spike recording from higher visual cortex in non-human primates



Visualization of functional maps with spatial resolution at electrode spacing (400μm)



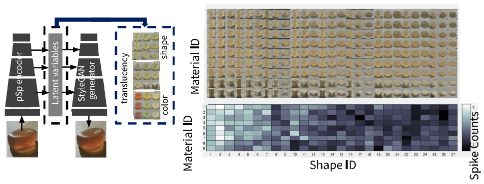
Odd-numbered segments: Viewed image →
Even-numbered segments: Reconstructed image →

Successful high-precision decoding of color, texture, shape, and category

(Fei, …, Nakada, …, Hayashi, arXiv 2025)

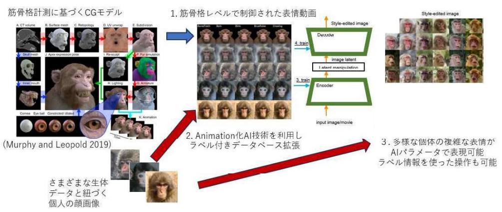
Decoding the Translucency of Objects Based on Neural Information

Among the types of information that are difficult to convey verbally, the shape and material properties of objects are particularly notable. Using a generative AI model trained on object images with varying degrees of light transmittance, we systematically produced images differing in both shape and transparency, and recorded neural activity while these stimuli were presented. This allowed us, for the first time, to measure how neural responses change as a function of variations in object shape and perceived translucency. Furthermore, by training AI models on the recorded neural data, we successfully predicted human transparency ratings from neural responses (Nakada, Nakamura, Hayashi, 2024).



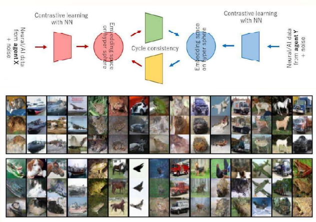
CA Development Using Generative AI

Using image-generation AI, we created a high-fidelity macaque avatar and developed a system that maps facial expressions—captured with a high-speed camera—onto the avatar in real time. The results of this work are currently under review in an international scientific journal (Igaue, …, Hayashi, under review). We are now extending this line of research to investigate avatar control based on emotion- and expression-related signals recorded directly from the brain.



Representation Transfer Technology for IoB

When transmitting information between different systems—such as brain-to-brain or brain-to-AI communication—it is necessary to "translate" between their respective representational formats. In collaboration with PM Kanai, we developed a brain-information communication technology that enables mutual translation without requiring explicit correspondence information between neural representations. In computational validation experiments, we demonstrated that images can be reconstructed with high fidelity using only the transfered information (Nakamura, …, Kanai, Hayashi, 2024; Patent Application No. 2022-152153).

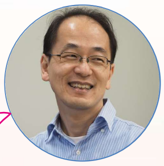


Top: Original image, Middle: Reconstructed image, Bottom: Reconstructed image after transfer

Future Prospects

We aim to further accelerate our research on human-function augmentation through X-Communication using brain and neural signals recorded from nonhuman primates. To enable the transmission of information that is difficult to convey verbally—such as material qualities, sensory impressions, and affective states—we will advance IoB research that integrates multimodal and generative AI. In parallel, we will pursue the development of a "digital brain," a computational model that precisely captures neural information processing, in order to enhance the accuracy of brain-signal decoding.

Furthermore, we will investigate the cognitive and neural changes induced by avatar manipulation, and develop methods for controlling network-level brain activity. Through these efforts, we aim to expand the technological foundations of the Internet of Brains (IoB).



Ryosuke Hayashi, Ph.D.

Senior Research Scientist

He is a Senior Research Scientist at the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, where he conducts research in visual neuroscience, visual psychophysics, and AI for image processing and image generation. He specializes in large-scale chronic neural recording techniques in non-human primates and is actively engaged in Internet of Brains (IoB) research and development leveraging advanced AI technologies. He also participates actively in joint research projects and international research collaborations.

Noriko Nakata Postdoctoral Researcher

Motofumi Shishikura Postdoctoral Researcher

Daiki Nakamura Former member

Hiroaki Kiyokawa Former member

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Estimation of Human State Using Indirect Biometric Information and Its Applications

Prof. Hideki Koike Institute of Science Tokyo

Overview

Estimating human posture and motor states is a crucial technology in fields such as rehabilitation and skill acquisition support. Although advanced state estimation using electroencephalography (EEG) holds promise for future applications, current EEG-based methods still face limitations in noise robustness and real-time performance, preventing their practical deployment. To address this challenge, the Koike Laboratory focuses on more stable and readily obtainable indirect physiological signals—such as electromyography (EMG), gaze information, and plantar pressure—and aims to develop posture estimation techniques based on these modalities (Fig. 1).

In this study, we concentrate specifically on plantar pressure sensing and seek to develop a high-precision method for three-dimensional posture estimation using only the information obtained from compact, wearable pressure sensors. By eliminating the need for costly and spatially restrictive optical motion-capture systems, our goal is to establish a real-time and versatile inference system suitable for practical use in real-world environments.

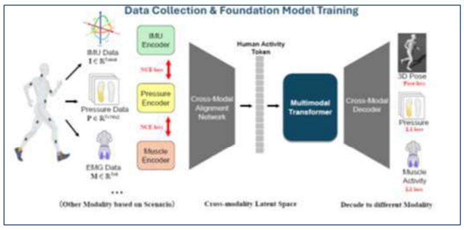
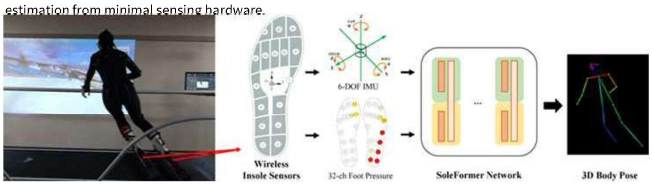


Fig 1　Overview of this entire study

SolePoser: From Foot Pressure to Posture

In this study, we propose SolePoser, a lightweight and real-time method for estimating full-body three-dimensional posture using only insole-type plantar pressure sensors. Conventional motion-capture systems require expensive camera setups or the attachment of numerous IMUs, which limits their applicability in daily-life settings and sports environments. In contrast, our method takes the plantar pressure distribution obtained from insole sensors as input and estimates the 3D positions of 17 body joints using a Dual-Stream Transformer architecture, SoleFormer. To ensure physically consistent and highly accurate estimation, we introduce two key components: a Dual Cycle Loss, which reconstructs IMU signals and plantar pressure from the predicted poses, and a Cross-Attention mechanism that emphasizes the relationships between IMU dynamics and pressure patterns. Together, these components enable stable and precise full-body pose estimation from minimal sensing hardware.



Furthermore, to evaluate posture estimation from plantar pressure, we constructed a new large-scale multimodal dataset. The SP-S dataset, specialized for sports movements, includes high-difficulty actions such as skiing, snowboarding, golf swings, and table tennis, comprising a total of 606K frames collected from 28 participants. The SP-E dataset, which focuses on daily activities such as walking and squatting, contains 302K frames obtained from 10 participants (mean age 25.9 years). Combined, the two datasets amount to 908K frames, achieving significantly greater diversity and scale than existing datasets such as TMM. Experimental results demonstrated that our method achieved an average joint position error of 65.3 mm for sports-motion data and 51.0 mm for everyday movements, with angular errors of 29.7° and 22.3°, respectively. The inference speed is 11 ms per frame (on an RTX 3090 Ti), indicating that the system is fully capable of real-time deployment.

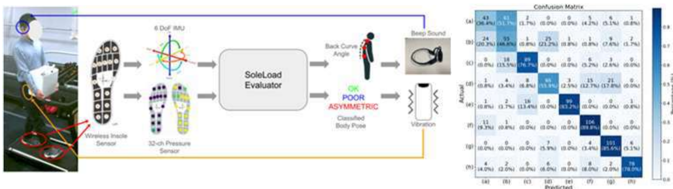
Network	Inference Time (ms)	Results w/o Elbow and Wrist (13 Joints)						Results w/ Elbow and Wrist (17 Joints)					
		SP-S		SP-E		TMM100 [40]		SP-S		SP-E		TMM100 [40]	
		MPJPE	MPJAE	MPJPE	MPJAE	MPJPE	MPJAE	MPJPE	MPJAE	MPJPE	MPJAE	MPJPE	MPJAE
PoseFormer (RGB) [70]	22.5	63.8	29.9	49.2	22.2	42.7	19.0	65.2	31.3	48.0	21.4	46.9	20.4
IMUPoser (2 IMUs) [31]	10.2	85.0	39.1	80.2	37.4	✗	✗	103.7	47.9	99.9	46.1	✗	✗
AvatarPoser (3 IMUs) [18]	6.1	74.6	37.6	69.7	31.3	✗	✗	70.7	34.9	66.7	30.0	✗	✗
Simple Foot IK [8]	5.0	119.3	49.3	100.7	46.7	✗	✗	135.3	56.6	118.5	53.3	✗	✗
Direct Transformer	8.7	72.2	35.3	69.5	31.0	✗	✗	87.6	40.3	77.4	36.6	✗	✗
PressNet (Inversed) [40]	38.9	87.3	40.9	82.8	38.2	54.3	25.8	94.4	44.6	89.9	41.9	59.7	27.5
SoleFormer (Pressure Only)	10.2	81.7	39.0	79.9	37.6	40.0	18.3	90.4	42.4	86.3	40.1	48.5	22.0
SoleFormer w/o CA	10.9	65.4	30.2	51.0	22.1	✗	✗	71.5	35.2	70.2	31.1	✗	✗
SoleFormer (Ours)	11.0	65.3	29.7	51.0	22.3	✗	✗	70.9	34.6	67.1	30.3	✗	✗

In comparative experiments, our method outperformed RGB camera–based approaches such as PoseFormer and IMU-based methods including IMUPoser and AvatarPoser, and substantially surpassed the existing plantar-pressure–based method PressNet. Ablation studies further demonstrated that incorporating plantar pressure input improved performance by 17 mm in average joint position error and by 8° in angular error compared to the use of IMU signals alone. We also confirmed that the introduction of Dual Cycle Loss and Cross-Attention contributed significantly to the overall accuracy improvements.

For real-world evaluation, we conducted validation experiments in alpine skiing and natural outdoor walking environments. As baselines, we compared against Xsens (using 17 IMUs) and third-person video captured using chest- and head-mounted cameras. The results showed that SolePoser achieved performance second only to TransPose and PIP, both of which rely on six IMUs, and exceeded RGB-based PoseFormer in skiing tasks. For walking motions, SolePoser matched the performance of PoseFormer, with only a 0.4 mm difference in joint position error.

These results were presented at the international conference UIST 2024[1].

SoleLoadEvaluator: Application to Posture Correction



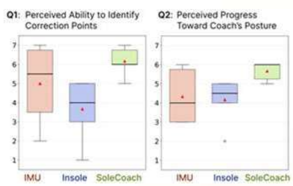
Building upon SolePoser, we propose SoleLoadEvaluator, a system that estimates forward-load walking posture using only plantar pressure sensors and provides real-time feedback. Conventional camera-based methods are sensitive to occlusions and environmental conditions, while multi-IMU configurations impose substantial wearing burden. In this study, we collected 8 types of load-bearing postures from 12 participants, constructing a dataset comprising approximately 670K frames.

In quantitative evaluations of posture classification and back flexion angle estimation, **the system achieved 72.4% accuracy for 8-class posture classification and a 7.3° error in flexion angle estimation**. Furthermore, adapting the model to a new user with one minute of personalized data increased performance to 82.4% accuracy and 4.2° error, demonstrating practical adaptability.

This system enables safe load-carrying assistance with minimal sensing hardware and low user burden, indicating strong potential for applications in industrial settings and rehabilitation. **This work was presented as an oral presentation at AHs 2025 [2].**

SoleAICoach: Multimodal Coaching

In this study, we propose SoleAICoach, a system that integrates plantar pressure sensing with a multimodal large language model (LLM) to automatically generate coaching feedback aimed at supporting skill acquisition [3]. While conventional coaching-support systems rely on cameras or motion-capture technologies, SoleAICoach directly converts plantar-pressure data into natural language feedback using an LLM, **enabling users to understand individualized points for improvement without requiring visual recording equipment**.



The dataset proposed in this study is **the first coaching dataset in which audio coaching comments, body posture, and plantar-pressure signals are fully synchronized**, comprising 3.1 million frames collected from 22 skiers.

In quantitative evaluations, the **similarity** between the generated coaching comments and those provided by expert coaches reached **85.2%**. User studies further demonstrated that participants were able to correct their own posture more effectively with feedback generated by SoleAICoach compared to conventional methods.

[1] Erwin Wu, Rawal Khirodkar, Hideki Koike, Kris Kitani, "SolePoser: Full Body Pose Estimation using a Single Pair of Insole Sensor", ACM Symposium on User Interface Software and Technology (UIST) 2024.
[2] Shino Ito, Yichen Peng, Erwin Wu, Hideki Koike, "SoleLoadEvaluator: A Real-Time Feedback System for Walking Posture with Anterior Load Using Insole Sensors", Augmented Humans (AHs) 2025.
[3] Toshihiro Hirano, Yuki Tabei, Yichen Peng, Chen-Chieh Liao, Erwin Wu, Hideki Koike, "SkiTechCoach: A Multimodal Alpine Skiing Dataset with 3D Body Pose, Sole Pressure, and Expert Coaching", ACM Multimedia (MM) 2025.

Future Prospects

Traditionally, skill acquisition has focused primarily on imitating the external appearance of experts, particularly their body posture. However, in the future, understanding internal physiological signals—such as EEG, EMG, and gaze—will become equally important. Although measuring such biosignals remains costly and technically demanding at present, developing methods that enable simplified measurement or estimation of these signals through computer vision and AI technologies will be essential.

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Professor Institute of Science Tokyo

He is a Professor at the School of Computing, Tokyo Institute of Science (formerly Tokyo Institute of Technology). He received his Ph.D. in Engineering from the University of Tokyo in 1991. His research focuses on Human-Computer Interaction (HCI), particularly Vision-based HCI using computer vision techniques. In recent years, as a principal investigator for projects such as JST CREST and JST ASPIRE, he has conducted research on skill-acquisition support for professional athletes, expert pianists, and surgeons using computer vision, AI, and VR/AR technologies. He has received the IEEE Best Paper Award, the Japan Society for Software Science and Technology (JSSST) Fundamental Research Award, and is a Fellow of the Information Processing Society of Japan (IPSJ).

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Internet of Brains

国立研究開発法人 科学技術振興機構 ムーンショット型研究開発事業 ／ 株式会社国際電気通信基礎技術研究所
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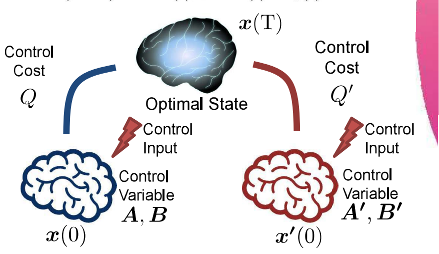
Theory of Brain Control

Associate Professor, Graduate School of Arts and Sciences,
The University of Tokyo
Masafumi Oizumi, Ph.D.

Overview

The brain can be considered a system that controls itself. If we can unravel the mechanisms of this control, it may become possible to guide the brain into desired states. We are currently working to elucidate the brain's controllability. For example, controllability during wakefulness should differ significantly from that during sleep or fatigue. One goal of this research is to investigate whether we can classify brain states based on these differences in controllability. Understanding the brain's controllability then allows us to approach the question of how to bring the brain closer to a desired state and what the optimal control might be. This represents another direction this research aims to pursue.



How the Brain can be Controlled?

1. System Identification via Perturbation (Ogino et al, bioRxiv, 2025): To realize brain control, it is necessary to model and estimate the temporal changes and dynamic characteristics of brain activity as accurately as possible. It has been found that achieving this accurate estimation is effective not only by observing brain activity but also by applying "perturbation inputs" and observing the brain's response. This is because perturbation makes the characteristics of dynamics that are inherently hidden and invisible become observable (Figure 1). We have developed a theory to investigate what kind of perturbation input should be applied to achieve the greatest improvement in identification accuracy. Based on this theory, system identification is most efficient when the frequency of the perturbation input matches the system's intrinsic frequency. These results also validate the effectiveness of brain state discrimination using stimulation techniques such as transcranial magnetic Stimulation (TMS). Moving forward, we will conduct verification studies, including the identification of effective perturbation inputs using real data.

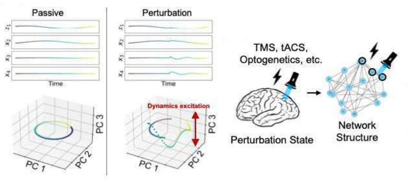


Figure 1. Excitation of invisible dynamics by stimulation Z

2. Classification of Brain States Based on Controllability (Shikauchi et al, bioRxiv, 2025): The brain can be viewed as a control system that transitions between states, such as shifting from a resting state to motor activity. This study proposed a simple method to estimate the controllability of brain states by introducing a control metric called the controllability Gramian (Figure 2). This method, grounded in control theory, utilizes the fact that the controllability Gramian is represented as the Gram matrix of the time-series data X during impulse stimulation. Introducing the controllability Gramian allows evaluation of both the ease of controlling a state (size of the Gramian eigenvalues) and the direction of control (direction of the Gramian eigenvectors). This enables a complete description of brain controllability along two axes: in which direction and to what extent control is possible. In data analysis, the proposed method was applied to transcranial magnetic stimulation (TMS)-electroencephalogram (EEG) data recorded during both active and resting states, characterizing a total of six distinct brain states from the perspective of controllability. The results revealed differences in the directionality of controllability across some brain states.

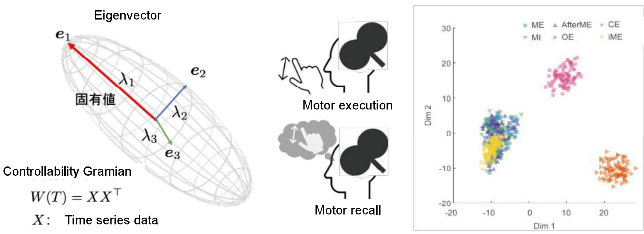


Figure 2. Eigenvalue decomposition of controllability Gramian and classifiability plot in motor tasks

Summary of Results

This study yielded the following results:

[1] Designing optimal perturbation inputs for system identification in neuroscience (Ogino et al, bioRxiv, 2025)

[2] Quantifying state-dependent control properties of brain dynamics from perturbation responses.→ Applied to EEG data for motor state discrimination (Shikauchi et al, bioRxiv, 2025)

[3] Optimal Control Costs of Brain State Transitions in Linear Stochastic Systems→ Applied to human fMRI data to quantify transition costs between task states and identify contributing regions (Kamiya et al, Journal of Neuroscience, 2023)

[4] Decomposing thermodynamic dissipation of linear Langevin systems via oscillatory modes and its application to neural dynamics→ Characterization of Arousal and Anesthesia States Using Monkey ECoG Data (Sekizawa et al, Physical Review X, 2024)

Future Prospects

We will apply the theoretical framework we have developed to actual neural data to verify whether brain states—such as fatigue levels and arousal levels—can be distinguished from the perspective of controllability. Furthermore, we believe this could lead to optimal intervention methods for guiding the brain into specific states and clinical applications for correcting abnormal controllability in the future.

Control Cost in Fluctuating Systems

3. Quantification of Stochastic Control Costs (Kamiya et al, Journal of Neuroscience, 2023): Quantifying control costs is essential for revealing how the brain can be controlled and which brain regions are most critical for regulating brain states. One challenge in elucidating brain controllability is that brain activity data are highly noisy and exhibit stochastic dynamics. Previous studies have largely ignored this probabilistic fluctuation, making accurate estimation of control costs difficult. This study constructs a new quantitative framework for control costs that accounts for the probabilistic fluctuation in neural dynamics. We established an analytical representation of the stochastic control cost and demonstrated that this cost can be decomposed into a mean control cost and a covariance control cost. The utility of the proposed metrics was confirmed using whole-brain imaging data from humans, identifying key brain regions involved in control transitions from the resting state to seven cognitive task states. Results revealed that the inferior visual cortex plays a common crucial role in average control across these transitions, while the posterior cingulate cortex plays a common crucial role in covariance control.

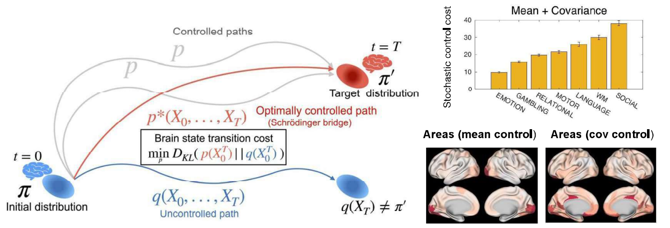


Figure 3. Control cost in brain state transitions and probabilistic systems

4. Thermodynamic Maintenance Cost (Sekizawa et al, Physical Review X, 2024): While the brain incurs control costs when changing from its current state to another state, it also incurs control costs to maintain its current state. This maintenance cost can be quantified by applying stochastic thermodynamics. We derived the relationship between neural oscillations in the brain and the entropy production rate used in stochastic thermodynamics. First, we mathematically demonstrated that the "housekeeping entropy production rate," which relates to maintaining the probability distribution within the total entropy production rate, can be decomposed into an independent positive contribution in an oscillatory representation (Figure 4). Specifically, the sum of the square of the oscillation frequency multiplied by the amplitude corresponds to entropy production.

This means that faster oscillating waves incur higher maintenance costs. Furthermore, applying the proposed method to monkey EEG data revealed clear differences in the contribution of oscillations between the awake and anesthetized states. Specifically, the contribution of delta waves increased in the anesthetized state, while the contribution of higher frequency components like theta waves decreased. This demonstrates that the characteristics of neural oscillations accompanying changes in brain state can be interpreted from a physical perspective involving thermodynamic dissipation and the limits of information processing.

Main Result

Housekeeping EPR, Frequency, Normalized intensity

$$\sigma_t^{\mathrm{hk}} = (2\pi)^2 \sum_k {\chi_k}^2 \sum_i (D_t^{-1})_{ii} (\mathsf{F}_k \Sigma_t \mathsf{F}_k^*)_i$$

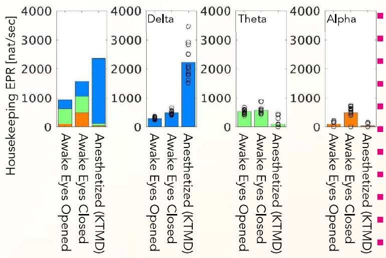


Figure 4. Decomposition of entropy production rate and its application to monkey EEG data

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Graduated from the Department of Physics, Faculty of Science, The University of Tokyo. Earned a Ph.D. from the Laboratory of Masato Okada, Graduate School of Frontier Sciences, The University of Tokyo. Assumed current position in April 2019. After obtaining his Ph.D., he was a member of the Shunichi Amari Team at the RIKEN Brain Science Institute until March 2017. From October 2011 to October 2013, he was a member of Giulio Tononi's laboratory at the University of Wisconsin-Madison. From April 2015 to October 2016, he was a member of Naotsugu Tsuchiya's laboratory at Monash University, Australia.From March 2017 to March 2019, he was a member of the Basic Research Group, Technology Department, at Araya Corporation.

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Mikito Ogino（Corresponding Presenter)
Project Researcher

Yumi Shikauchi — Project Researcher (at the time)
Shunsuke Kamiya — Ph.D. Student (at the time)
Daichi Sekizawa — Ph.D. Student

Internet of Brains

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IoB Middleware

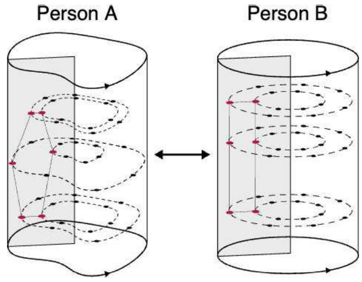
Moonshot Research and Development Program Goal 1 Kanai Project

Is the Quality of Subjectivity the Same or Different Between Individuals?

Associate Professor, Graduate School of Arts and Sciences, The University of Tokyo
Masafumi Oizumi, Ph.D.

Overview

When two people look at the same thing, are the qualities of their subjective experience the same? Or are they different? If they are different, how do they differ? By focusing on equivariance in information processing systems, we have developed a theory that predicts which aspects of subjective quality (qualia) are common across individuals and which may differ from person to person. Based on this theory, we predict that the aspects of qualia common across individuals correspond to how the system behaves equivariant. Outside this equivariance, qualia can differ from person to person. Alongside proposing this theory, we also introduce a new research paradigm for studying human subjective qualities under this framework.



Decomposition of Qualia: Rigid Qualia × Plastic Qualia

1. Consistency between the structure of qualia and the structure of neural activity

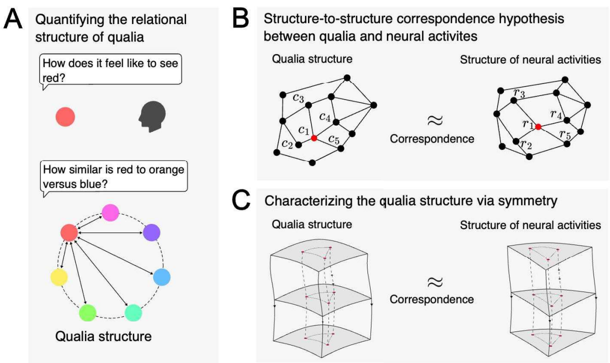


Figure 1. An approach to qualia focusing on structure

2. Decomposition of Qualia via Equivariance: Rigid Orbit × Plastic Quotient Space

Equivariance is defined with respect to transformations applied to a system's input. A system is said to be equivariant to a given input transformation when its processing commutes with that transformation (Figure 2). Focusing on equivariance enables us to treat different systems within a unified framework. In understanding systems through the lens of equivariance, we examine their behavior from two aspects.

One concerns transformations the systems are equivariant to (the orbit: geometry of qualia attributes). The other concerns they are not (the quotient space: geometry of qualia signatures) (Figure 3). When two systems share equivariance to the same transformation, they exhibit the same topology in the output trajectories generated by applying that transformation to a seed input (the main result of this research). In other words, equivariance ensures behavioral alignment between systems in that equivariance.

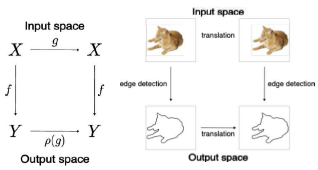


Figure 2. Definition of equivariance

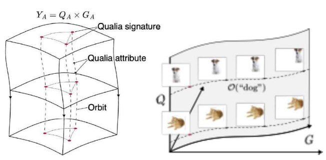


Figure 3. Decomposition by orbit and quotient space

Proposed Research Paradigm

3. Comparison Across the Entire Structure of Qualia

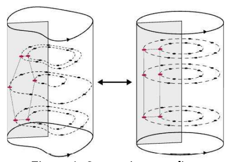


Figure 4. Comparison qualia structure on entire space

Based on our decomposition of qualia, we propose a new research paradigm for understanding how the qualia structures of two individuals are similar and how they differ. In this paradigm, we analyze similarity both at the level of the entire structure (Figure 4) and at the level of its decomposed components (Figure 5). This approach allows us to systematically examine not only the extent to which the two individuals' qualia structures resemble each other, but also how they are similar.

4. Comparing by breaking down the structure

First, we compare rigid qualia (the orbit). It may reflect natural transformations that occur in the external world, such as translation or rotation. Next, we compare plastic side (the quotient space). It may reflect an individual's innate characteristics and past experiences, giving rise to differences between individuals.

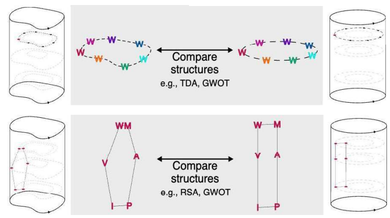


Figure 5. Comparison by breaking down the structure

Validation with Color equivariant Neural Networks (Color-equiv. NN)

Our theoretical results predict that two systems sharing the same equivariance will exhibit greater behavioral alignment in comparisons on the orbit than systems that do not share it. Additionally, our results predict that two equivariant systems will exhibit differences in comparisons on the quotient space to a similar extent as two non-equivariant systems do.

To validate these theoretical predictions, we examined the behavioral alignment of two pairs of neural networks: a color-equiv. pair and a non-color-equiv. pair. In comparisons over the entire color space, the color-equiv. networks exhibited more similar outputs than the non-equiv. ones to color stimuli. We then analyzed their behavior on the orbit (changes in hue) and on the quotient space (changes in saturation and lightness). In the orbit comparisons, the color-equiv. networks showed higher behavioral similarity than the non-equiv. ones. Conversely, in the quotient space comparisons, both pairs showed similar levels of behavioral similarity (Figure 6).

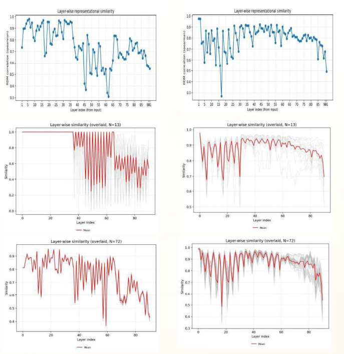


Figure 6. Effect of equivariance on orbit and quotient space

Summary of Results

In this study, we developed a theory predicting where subjective qualities share commonalities and differences between individuals, while simultaneously proposing a new experimental paradigm based on that theory. (Oizumi, Lim, and Kanai. Principal Bundle Geometry of Qualia: Understanding the Quality of Consciousness from Symmetry. PsyArXiv, 2025)

Future Prospects

The results presented here are still theoretical predictions about qualia, supported only by preliminary *in-silico* experiments. As a next step, we aim to validate these predictions using real-world data. We believe this research will contribute to technologies that can more clearly convey what "I" feel. At the same time, we expect it to provide a foundation for understanding how we communicate—specifically, what aspects of our subjective experience are shared and what aspects can differ—from the perspective of the brain's information-processing mechanisms. We hope this work will contribute to deeper mutual understanding of the subjective experiences held by different individuals, and we intend to advance our research with this goal in mind.

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Graduated from the Department of Physics, Faculty of Science, The University of Tokyo. Earned a Ph.D. from the Laboratory of Masato Okada, Graduate School of Frontier Sciences, The University of Tokyo. Assumed current position in April 2019. After obtaining his Ph.D., he was a member of the Shunichi Amari Team at the RIKEN Brain Science Institute until March 2017. From October 2011 to October 2013, he was a member of Giulio Tononi's laboratory at the University of Wisconsin-Madison. From April 2015 to October 2016, he was a member of Naotsugu Tsuchiya's laboratory at Monash University, Australia.From March 2017 to March 2019, he was a member of the Basic Research Group, Technology Department, at Araya Corporation.

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IoB Middleware

Moonshot Research and Development Program Goal 1 Kanai Project

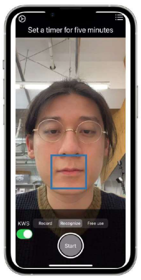
Silent Communication

Professor, Interfaculty Initiative in Information Studies, The University of Tokyo
Sony Computer Science Laboratories Inc. Fellow / CSO Rekimoto Jun

Overview

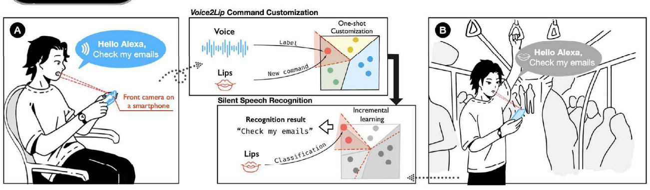
Voice-based communication, such as conversations with AI agents and remote communication, is becoming a major trend in next-generation HCI (Human-Computer Interaction). However, there are many situations where speaking is not possible, such as in public settings, and confidentiality cannot be guaranteed. Speech intent recognition via BCI requires invasive brain procedures and has not yet achieved recognition speeds or accuracy at normal conversational rates. This project aims to establish “Silent Communication” technology that recognizes speech from silent or near-silent, minimal vocalizations using deep learning. This technology will usher in the world of think communication, enabling users to enhance their thinking through conversation with AI anytime, anywhere. Additionally, we are researching the mechanisms of brain synchronization during remote communication and combining gaze with MLLM to enable AI to understand human advanced skills.

LipLearner: Speaker-independent lip reading



LipLearner is a silent speech technology based on lip reading. While conventional lip reading required speaker-dependent learning, this research applied the CLIP (Contrastive Language-Image Pretraining) method to lip reading, achieving speaker-independent recognition. Furthermore, by developing a mobile version that runs on smartphones, it contributed to realizing silent speech that can be used anytime, anywhere.

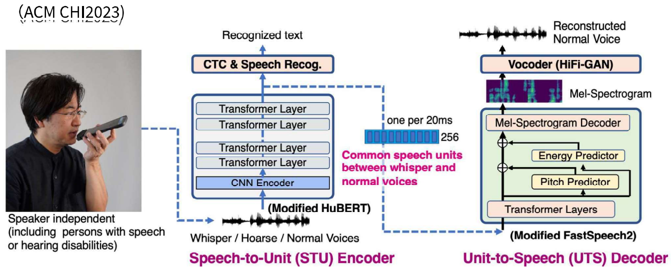
(ACM CHI2023 best paper)



WESPER: Real-time Whisper Voice Conversion

Whispered speech using minimal audio is also a promising means of silent communication. In this study, by pretraining on a large volume of whispered speech, we enable conversion from minimal audio to normal speech by extracting speech units independent of specific languages or speaking styles.

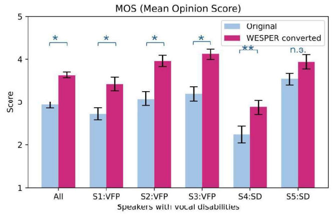
(ACM CHI2023)



Speech Support for Individuals with Voice Disorders

We conducted research on speech support for individuals with voice disorders using AI-based voice conversion technology. By converting the voices of people who have difficulty producing normal speech due to various factors—such as laryngectomy, vocal cord polyps, dystonia, or hearing impairment—into their natural voices, we achieved significant improvements in sound quality. We are aiming to develop technology that combines voice cloning with this approach to restore each person's original voice.

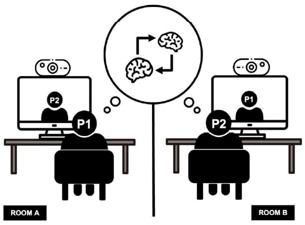
(ACM CHI2023)



VFP: vocal fold polyp (声帯ポリープ)
SD: spasmodic dysphonia (痙攣性発声障害)

Elucidation of Remote Brain Synchronization Mechanisms

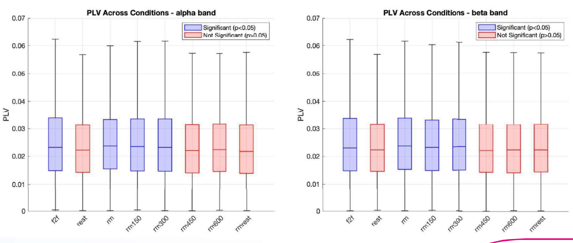
It was known that brain waves synchronize among people engaged in collaborative tasks, but whether brain synchronization occurs in remote environments remained unknown. In this study, by measuring brain synchronization in a remote environment with controlled communication delays, we confirmed that brain synchronization occurs during collaborative tasks in environments with delays of 450 milliseconds or less.



This clearly demonstrates that brain synchronization arises from interactions between brains, not external factors.

This finding is expected to be applied to metrics such as the quality of collaborative work in remote environments.

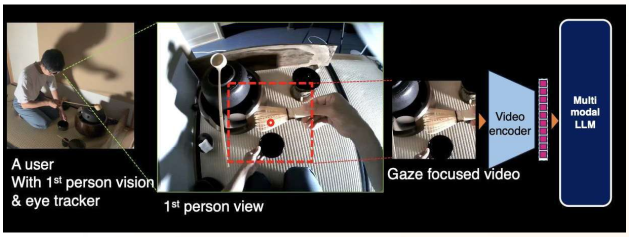
(Augmented Humans 2025)



GazeLLM: Multimodal LLM Utilizing Gaze

We are building a mechanism to directly teach first-person perspective video to MLLM (Multimodal Large Language Models) and transmit human skills to others via AI. By incorporating gaze information, we confirmed that reflecting the skilled operator's attention into the LLM improves action comprehension accuracy.

(Augmented Humans 2025)



Future Prospects

The major future trend in HCI (Human-Computer Interaction) is the fusion of humans and AI. The silent communication being advanced in this project aims to build a world where conversation with AI is possible anytime, anywhere, and where human thought is naturally enhanced by AI.

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Ph. D Student

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Qing Zhang, Ph.D.
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Internet of Brains

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Moonshot Research and Development Program Goal 1 Kanai Project

IoB Middleware

Beyond Symbolic Interfaces: Dual-Task Navigation Support Using Perceptual Information from Motion

Professor, Interfaculty Initiative in Information Studies, The University of Tokyo
Sony Computer Science Laboratories Inc. Fellow / CSO Rekimoto Jun

Overview

Conventional pedestrian navigation relies on symbolic instructions displayed on screens, demanding visual attention from users and making it difficult to perform secondary tasks simultaneously. This study addresses this issue by proposing a wearable directional guidance method that operates without symbols, instead engaging human “kinesthetic perception.” By presenting kinesthetic cues such as haptic feedback through a body-worn device, users can intuitively grasp direction without diverting their gaze. Experimental evaluation demonstrated that the proposed method statistically significantly improves performance on secondary tasks compared to conventional visual symbol-based guidance, while maintaining navigation performance. These results contribute to the design of non-symbolic interactions that enable safer and more efficient dual-task environments.

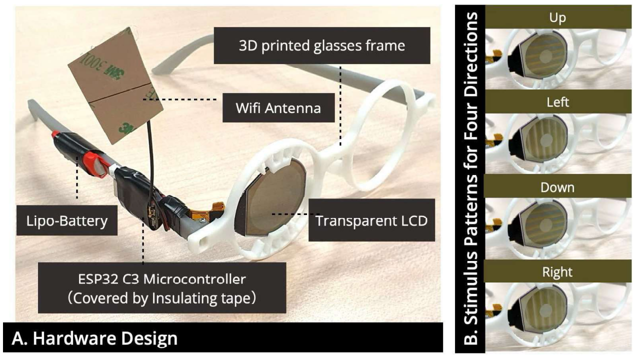

Figure 2: This shows the prototype of the developed wearable device and an image of the light displayed on its screen. (A) This shows the device's internal structure. The frame, which forms the glasses' skeleton, was created using a 3D printer. A transparent liquid crystal display (LCD) is integrated into the lens section on the right. Inside, it houses a small computer (ESP32-C3) that serves as the brain controlling the entire device, a power battery, and a Wi-Fi antenna for wireless communication. (B) This shows the pattern of “motion” displayed on the transparent screen in a frame-by-frame sequence. The brain perceives this as “motion” because the light bars appear to move smoothly. As an example, it illustrates how the four basic directions—up, down, left, and right—are conveyed through distinct light movements.

Background

The proliferation of mobile computing and wearable technology has made navigation assistance accessible to anyone, anywhere. However, the current mainstream approach relies heavily on visual “symbols” such as maps and arrows displayed on smartphone or smartwatch screens. This paradigm inherently poses challenges because it forces users to frequently stare at the screen.

First, human visual attention is a finite resource, and navigation information competes with the surrounding physical environment (other pedestrians, obstacles, traffic signals, etc.) for this resource. This competition significantly reduces the user's situation awareness, increasing risks such as collision accidents. Second, this visual dependency hinders the performance of secondary tasks (dual-tasking) that users naturally wish to perform while moving, such as enjoying scenery at tourist spots or conversing with friends. This is because the sequence of processes—recognizing symbols, interpreting their meaning, and converting that into action—imposes a non-negligible cognitive load on the user.

Therefore, this research aims to redefine a new form of wearable navigation that can support dual tasks more safely and efficiently without consuming limited visual resources, thereby addressing this fundamental challenge of “visual symbol dependency.”

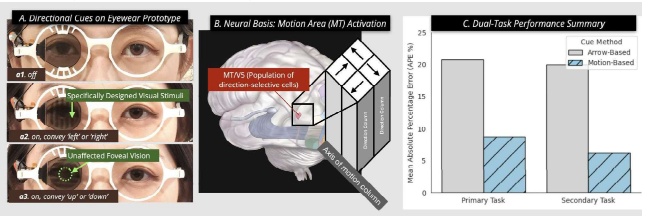

Figure 1: This figure shows our newly developed system that uses “motion” to indicate direction and summarizes the results of its performance evaluation. (A) This shows the device in actual use. A light bar moves at the edge of the field of view to indicate direction, allowing users to understand direction without disrupting the central part of the visual field (used for focusing on something) and while keeping their gaze forward. (B) This diagram illustrates the neuroscience mechanism of the system. It is designed so that the “motion” stimulus entering from the periphery directly activates the brain's specialized motion-sensing sensor area (known as the MT field in technical terms). This enables intuitive directional understanding without conscious thought. (C) This graph compares performance during multitasking. Compared to the conventional method of indicating direction with arrows, our motion-based method resulted in fewer errors during tasks (measured by APE: Average Percentage Error).

Results & Purpose

To verify the effectiveness of the proposed method, we conducted a dual-task experiment where participants simultaneously performed pedestrian navigation (primary task) and a visual cognitive task (secondary task), using conventional visual cues (arrows on a smartphone screen) as the control group.

Results: The experiment revealed no significant difference between the two methods in primary task performance metrics such as navigation task completion time and route accuracy. However, for performance on the secondary task (accuracy rate, reaction time), participants using the proposed method demonstrated statistically significantly higher performance. Furthermore, in the post-experiment subjective evaluation questionnaire, the proposed method received significantly higher ratings than the conventional method on items such as “lower cognitive load,” “easier to pay attention to surroundings,” and “feels safer.”

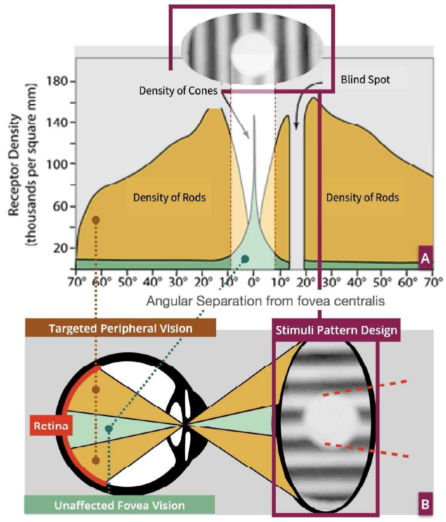

Figure 3: This diagram illustrates how we designed the light pattern to match the structure of the eye. (A) It shows the distribution of light-sensitive cells in the “retina,” located at the back of the eye. The central area is densely packed with “cone cells,” which are good at seeing fine details and colors. Meanwhile, the surrounding peripheral area contains numerous “rod cells” that are sensitive to light and motion. (B) Our light pattern design cleverly utilizes this mechanism of the eye. It targets the “peripheral area of the eye,” where motion-sensitive cells are concentrated, to present motion information. This allows us to convey only the necessary information without interfering at all with the “central area of the eye,” which is most critical for seeing objects.

Approach

This study focused on human “motion perception” as a more direct, physical channel of information transmission that does not require the cognitive “decoding” process of symbols. This is a fundamental ability acquired by organisms through evolution to detect and interpret movement quickly and with low cognitive load.

Applying this principle, we designed and developed a wearable device that generates motion perception cues. The prototype is a band-type device worn on body parts like the wrist or waist, containing multiple tactile actuators (ultra-small vibration motors) arranged linearly at equal intervals. To indicate direction, these actuators are activated in specific spatiotemporal patterns (e.g., sequential activation from left to right at 0.1-second intervals). This generates a distinct phantom sensation on the user's skin, as if something were smoothly “moving” across it.

Users can navigate intuitively by simply moving toward the perceived direction of this “motion.” This method not only achieves complete Eyes-Free operation without any visual input but also minimizes cognitive load by bypassing higher-order cognitive processes associated with symbol interpretation. Consequently, users can freely allocate their cognitive resources to environmental awareness and secondary tasks.

Academic Significance: This study demonstrated the effectiveness of “Perception-Centric Design” in wearable HCI (Human-Computer Interaction), overcoming the limitations of conventional symbolic information presentation. It showed that the information channel of kinesthetic perception is highly efficient, particularly in resource-constrained mobile environments, providing a new theoretical foundation for future non-symbolic interface design.

Qing Zhang
Interfaculty Initiative in Information Studies, The University of Tokyo
Project Assistant Professor
Our research centers on integrating artistic and design methodologies with cutting-edge human-centered technology. We develop wearable systems that enhance human experiential value to address societal challenges such as fostering empathy in inclusive design, preserving expert skills, and enabling human-AI co-creation.

Junyu Chen Master’s Student
Graduate School of Information Science and Technology, The University of Tokyo

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REKIMOTO LAB
Laboratoire Révolutionnaire et Romantique

Internet of Brains

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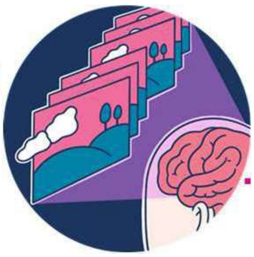
IoB Core Technology

Moonshot Research and Development Program Goal 1 Kanai Project

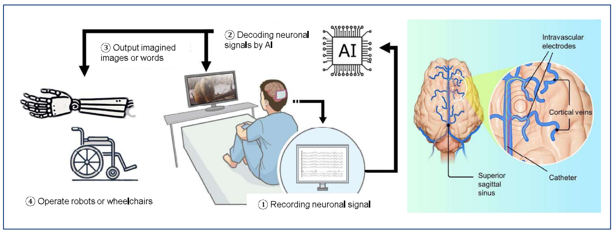


Development for Clinical Application of Invasive BMI

Takufumi Yanagisawa, M.D., Ph.D.
Professor, the Department of Neuroinformatics, Osaka University Graduate School of Medicine

Overview

We aim to realize a society in which individuals with severe paralysis—such as those with amyotrophic lateral sclerosis (ALS)—can participate socially by controlling cybernetic avatars (CAs) solely through brain activity. To achieve this, we are developing next-generation BMI technologies that enable high-precision measurement of neural signals and accurate decoding of human thoughts and intentions—specifically, 1. We have developed a method for reconstructing imagined images from intracranial EEG signals recorded via electrodes implanted within the skull. 2. We have also established a minimally invasive technique for acquiring high-fidelity intracranial EEG from within the blood vessels, eliminating the need for craniotomy while maintaining high signal precision. 3. Furthermore, we demonstrated that long-term implantation of neural recording devices enables stable measurement of brain activity, thereby allowing BMIs to operate with sustained reliability over extended periods. These advances collectively pave the way for the practical deployment of next-generation BMIs that support autonomous action and communication for individuals with severe motor impairments.



Development of Brain Information Decoding Technology Using Intracranial Electroencephalograms

We have developed technologies that decode human intentions, recall, and thought content from intracranial EEG (iEEG), and applied them to communication through brain–machine interfaces (BMIs). Notably, we developed a BMI capable of reconstructing the semantic content of imagined images with over 80% accuracy using human iEEG signals (Fig. 1). In this system, we employed the AI model CLIP to represent the meaning of an imagined image as a semantic vector. The system then searched a database of 2.3 million images online and displayed the image whose semantic representation was closest to the decoded vector (Fukuma et al., Communications Biology, 2022; Fukuma et al., under review). Furthermore, using the decoded semantic vectors, we successfully generated both sentences and images (Ikegawa et al., Journal of Neural Engineering, 2024). Additionally, by analyzing long-term intracranial EEG recordings, we identified brain activity associated with spontaneous thoughts experienced in daily life. In particular, we demonstrated for the first time worldwide that sharp-wave ripples (SWRs)—characteristic hippocampal oscillations essential for memory consolidation—are associated with mind-wandering, a form of spontaneous thought (Iwata et al., Nature Communications, 2024; Fig. 2). Together, these findings demonstrate the potential for BMIs capable of decoding and

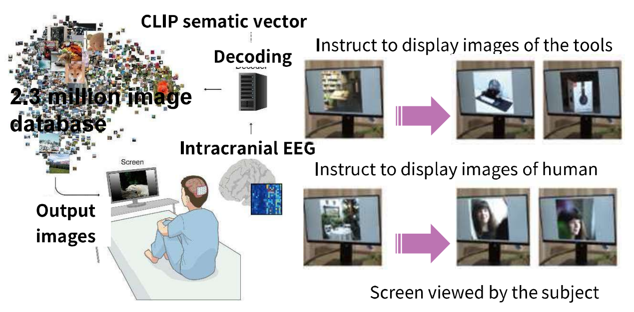


Figure 1. During intracranial EEG recording, participants were instructed to imagine one of two categories of images—either tools or humans—while viewing a screen. From the iEEG signals, the semantic content of the imagined image was decoded, and the system searched a database of 2.3 million images to display the image with the closest semantic representation on the screen every 250 ms. While viewing the output images, participants continued to imagine the instructed category so that the displayed images would match the target meaning. For the two instruction categories, two out of the three participants achieved an accuracy of over 80%.

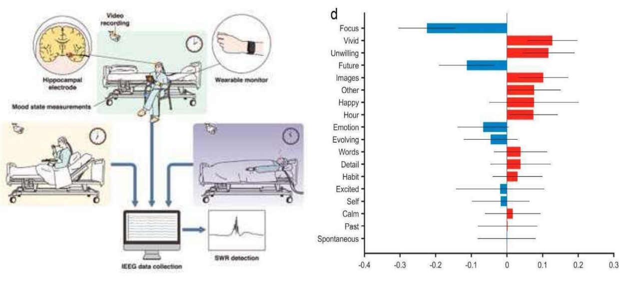


Figure 2. Intracranial EEG and wearable device measures (including activity level and heart rate) were continuously recorded for over 10 days, while participants' thought content was assessed every hour. Sharp-wave ripples (SWRs) were recorded from hippocampal electrodes, and fluctuations in SWR frequency were modeled using mixed-effects analyses with thought content, activity level, and heart rate as explanatory variables. The results showed that variations in SWR frequency were best explained by thought content, with SWRs increasing particularly during periods of mind wandering, when participants were not focused on the current task.

Development of a BMI Using Intravascular Electroencephalography

In conventional intracranial EEG (iEEG) procedures, electrodes must be implanted through a craniotomy performed under general anesthesia. However, for patients with severe neurological disorders such as ALS, general anesthesia poses substantial risk and physical burden. Thus, there is an urgent need for methods that can obtain high-precision intracranial signals without craniotomy and under local anesthesia. We aim to develop an minimally invasive BMI in which electrodes are delivered intracranially via blood vessels using a catheter, without opening the skull. Traditional intravascular electrodes were rigid, limiting recordings to the superior sagittal sinus that runs along the midline of the cortex, making it difficult to capture signals from broader cortical regions—such as hand and orofacial motor areas—that are crucial for BMI applications. To overcome this limitation, in collaboration with the minimally-invasive group, we developed flexible, ultrathin intravascular EEG electrodes, enabling us to successfully record intracranial signals from cortical surface veins, a feat previously considered technically unattainable. In porcine experiments, electrodes placed in cortical surface veins successfully captured high-resolution evoked responses (SEPs and VEPs), with signal amplitudes exceeding those recorded simultaneously from ECoG. Moreover, stimulation through venous electrodes positioned over the motor cortex elicited muscle responses in the face and forelimb (Iwata et al., Advanced Intelligent Systems, 2025).

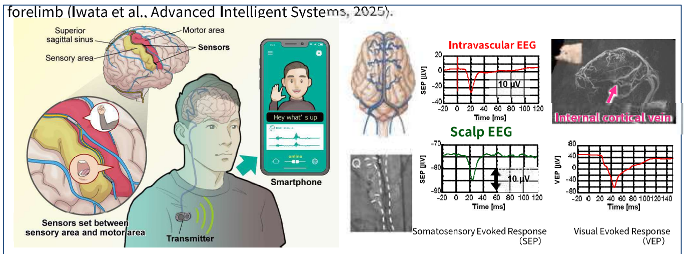


Figure 3. (Left) Conceptual illustration of an ultra-thin intravascular EEG-based BMI. Intracranial EEG is recorded from electrodes placed near the hand and orofacial motor cortices via small cortical veins. The signals are transmitted to an external receiver through a subcutaneously implanted transmitter in the chest. Decoding these signals enables control of a cybernetic avatar (CA). (Right) In experiments using pigs, somatosensory evoked potentials were successfully recorded from cortical surface veins, with amplitudes higher than those obtained simultaneously from ECoG. Furthermore, we successfully recorded intravascular EEG from deep brain regions—where electrode placement via craniotomy is technically challenging—and detected clear visual evoked responses.

Safety and Efficacy Evaluation of Implantable ECoG Devices

We evaluated the safety and efficacy of an implantable neural recording device that connects to the aforementioned intravascular electrodes and wirelessly transmits brain signals from inside the body. Specifically, a clinically applicable device was implanted in two Japanese macaques, and we demonstrated stable cortical signal recording for more than two years. By conducting motor and sensory tasks over extended periods and training models on the resulting large-scale datasets, we showed that BMIs could be achieved with robust and reliable accuracy. Notably, using deep learning, we found that decoding performance improved according to a logarithmic law with increasing data volume (Fig. 4).

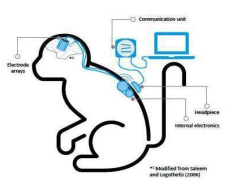


Figure 4. The implantable neural recording device placed inside the monkey's body wirelessly transmits intracranial signals and is powered wirelessly. The decoding accuracy of deep learning models improved according to a logarithmic scaling law with respect to the amount of training data. Using the trained models, we confirmed the successful implementation of BMI control.

Future Prospects

We aim to translate intravascular EEG–based BMI technology into a medical device and deliver BMI-based communication and cybernetic-avatar (CA) control to patients with severe paralysis, such as those with amyotrophic lateral sclerosis (ALS). In the future, we also envision applying these technologies to support mental and physical well-being, including applications in stress monitoring and autonomic nervous system regulation.

Takufumi Yanagisawa, M.D., Ph.D.

Professor, the Department of Neuroinformatics, Osaka University Graduate School of Medicine

After completing his M.S. in Science and Engineering at Waseda University in 2000, he transferred to the Faculty of Medicine, School of Medicine, Osaka University, and graduated in 2004. Following initial clinical training in neurosurgery, he developed electrocorticography (ECoG)-based brain–machine interfaces and obtained his Ph.D. in Medicine from the Graduate School of Medicine, Osaka University, in 2009. He was appointed Assistant Professor at the Graduate School of Medicine, Osaka University, in 2012. In 2013, he received the Young Scientists' Prize, a Commendation for Science and Technology, from the Minister of Education, Culture, Sports, Science and Technology (MEXT). In 2016, he became a Lecturer in the Division of Clinical Neuroengineering at the Center for Information and Medical Engineering, Osaka University, and in 2018, he was appointed Professor at the Institute for Advanced Co-Creation Studies, Osaka University. He has held his current position since 2024.

Yang Huixiangms
Specially Appointed Assistant Professor, the Department of Neuroinformatics, Osaka University Graduate School of Medicine

Ryohei Fukuma
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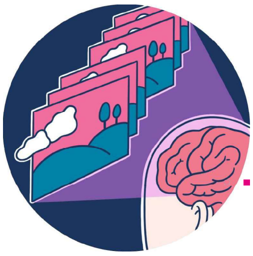

An ECoG–BCI for Virtual Embodiment

Chang Lab, Weill Institute for Neurosciences - University of California, San Francisco, USA.

Overview

Brain-computer interfaces (BCI) have the potential to facilitate high-bandwidth information transfer between users and technology. As a part of the UCSF BRAVO (BCI Restoration of Arm and Voice) clinical trial, we recorded neural activity directly from the surface of the brain using electrocorticography (ECoG). Here, we show that both speech and facial movements can be decoded directly from the neural activity of individuals with severe vocal-tract and bodily paralysis, and used to subsequently animate a virtual avatar. These findings form a key proof-of-concept demonstrating the potential for naturalistic, embodied communication through BCI-controlled virtual avatars.

ECoG-BCI control of a personalized facial avatar

- Embodied communication is comprised of not only speech outputs, but also intonation, expressiveness, and identity.
- Therefore, in addition to decoding speech output, decoding the accompanying facial expressions and synthesized speech are necessary steps towards a naturalistic speech neuroprosthesis.
- Towards this goal, we designed a three-component, multimodal decoding system capable of decoding speech output as text and synthesized audio, as well accompanying facial and vocal tract movements.
- This articulatory-gesture decoding system used deep, recurrent neural network modeling.
- While speech output as text was incrementally decoded, synthesized audio and facial expressions were decoded after the participant was done speaking, leading to latencies around 8 seconds.
- A combination of high and low frequency features from neural activity from the sensorimotor cortex (SMC) are decoded into flexible but discrete latent articulatory gesture units, which then animate a facial avatar.
- The facial avatar can be used alongside speech attempts or in isolation, such as to convey emotional expressions.
- The avatar (Speech Graphics, Unreal Engine 4.26) is personalized to resemble the participant.
- For further details and figures, see the published paper “A high-performance neuroprosthesis for speech decoding and avatar control” in *Nature* (https://doi.org/10.1038/s41586-023-06443-4).

Towards streaming speech synthesis and articulatory control

- Though our prior work was the first successful demonstration of high accuracy speech synthesis from neural activity during silently attempted speech, the high latencies are prohibitive to natural conversation.
- Ideally, synthesized speech and facial movements would be decoded and played or animated in real time.
- Towards this goal, we developed a speech decoding framework capable of streaming synthesized speech output.
- This model used a recurrent neural network transducer framework, enabling the model to learn both a neural encoder and implicit speech models that can act as a streaming version of a language model over latent units.
- This framework achieved faster decoding speeds (47.4 versus 28.3 words per minute) and lower latencies (1.7 versus 8.0 seconds), compared to prior work, while still maintaining a similar level of accuracy (45.3% versus 45.7% word error rate).
- Combined with our prior work showing that facial movements can be decoded from the same neural signals, future work may apply this same framework to decoding facial movements with low latencies.
- For further details and figures, see the published paper “A streaming brain-to-voice neuroprosthesis to restore naturalistic communication” in *Nature Neuroscience* (https://doi.org/10.1038/s41593-025-01905-6).

Future Prospects

Together, these findings demonstrate that an ECoG-BCI can be used to animate a virtual avatar alongside speech decoding. This work is an important step towards naturalistic, embodied neuroprostheses. Expanding the avatar to larger movement repertoires using continuous control and increasing the speed of the system are important future research directions.

Edward F. Chang, MD
Professor and Chair of Neurosurgery

In addition to being the Joan and Sanford I. Weill Chair of the Department of Neurological Surgery at UCSF, E.F.C. is the Jeanne Robertson Distinguished Professor at the UCSF Weill Institute for Neurosciences, the Co-Director of the UC Berkeley-UCSF Center for Neural Engineering and Prostheses, and a Chan Zuckerberg Biohub Investigator.

BRAVO Research Team: Jessie R. Liu, PhD; Samantha C. Brosler; Irina P. Hallinan; Alexander B. Silva, PhD; Cady M. Kurtz-Miott; Jonah Dunkel Wilker.

国立研究開発法人 科学技術振興機構 ムーンショット型研究開発事業 ／ 株式会社国際電気通信基礎技術研究所
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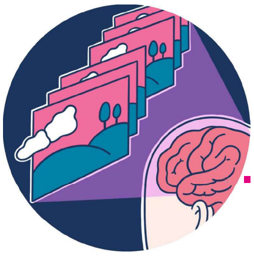
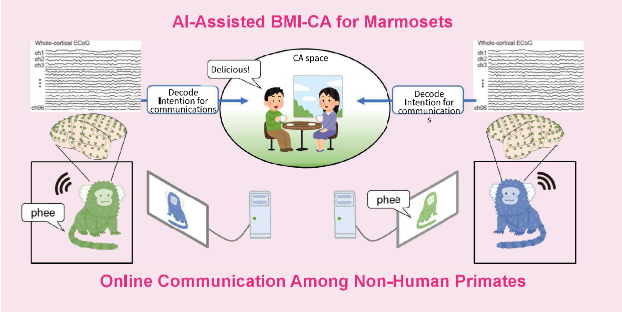


Core Technology for Intent Communication

Misako Komatsu, Ph.D., Specially Appointed Associate Professor, Institute of Integrated Research, Institute of Science Tokyo

Overview

Komatsu Group develops an intent-communication environment for animals and seeks key features required for intention decoding by applying AI to invasive, non-invasive, and contact-free signals in an integrated manner. Through recording signals ranging from highly informative invasive neural activity to fully contactless modalities, we can systematically evaluate the required level of invasiveness for a given application. The project provides the core IoB technologies toward realizing a cybernetic avatar with brain–machine interface capabilities (BMI-CA).



Shaping the future of primate research

~Large-Scale Neural Dynamics in Freely Behaving Primates~

Komatsu Group is developing invasive brain–machine interfaces (BMIs) using nonhuman primates, common marmosets. In particular, we focus on decoding contents of thoughts and intentions, and on delivering the information directly into the brain.

Traditionally, primate neuroscience requires restraining the animal during neural recording, which limits the observation of natural behavior and restricts the duration of experiments. We were the first in the world to successfully record large-scale neural activity across the entire lateral hemisphere of freely moving marmosets (Fig. A). This breakthrough enables long-term, high-resolution recording of neural activity during natural movements and vocal communication between marmosets. Acquiring high-precision neural data at large scale is a fundamental technological component for all BMI development.

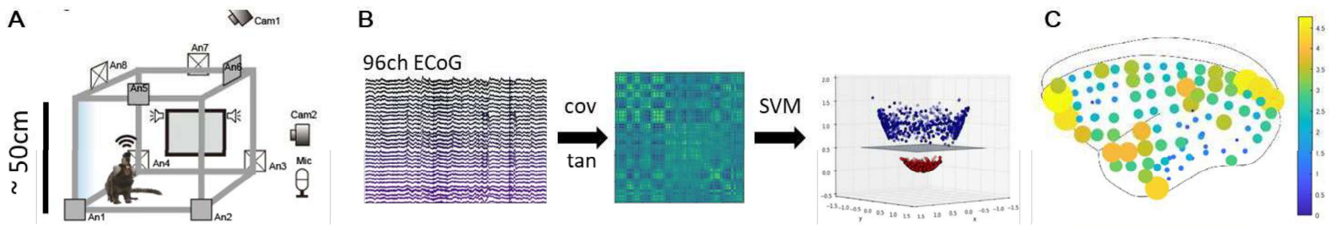
Beyond BMI research, primate models are essential for understanding advanced human brain functions—such as empathy, consciousness, and language—as well as the mechanisms underlying psychiatric disorders. In recently, ethical concerns have reduced primate research in Europe and the United States. However, our newly developed technology for large-scale neural recording in freely behaving marmosets imposes minimal burden on the animals and is poised to become a new standard in future primate neuroscience.

Higher brain areas contribute to decoding multimodal intentions

BMIs are expected to help people who are unable to move their bodies due to illness or injury operate prosthetic limbs or communicate their thoughts when speech is impaired. However, current BMIs often handle only limited types of actions. To broaden their applications, BMIs must accurately decode multiple modalities of intention, such as those related to movement and vocalization.

Using our large-scale neural recording technology in marmosets, we captured extensive brain activity during natural vocal communication and spontaneous movement. At the same time, we recorded behavior with cameras and vocalizations with microphones, and collaborated with the Sasai Group to develop a decoder which predict body movements and vocal call types from preceeding neural activity. We found that higher-order cortical regions, known as association areas, play a key role in decoding both future movements and vocalizations. This suggests that the brain may process motor and vocal intentions in overlapping regions, and that such intentions can be extracted directly from neural activity.

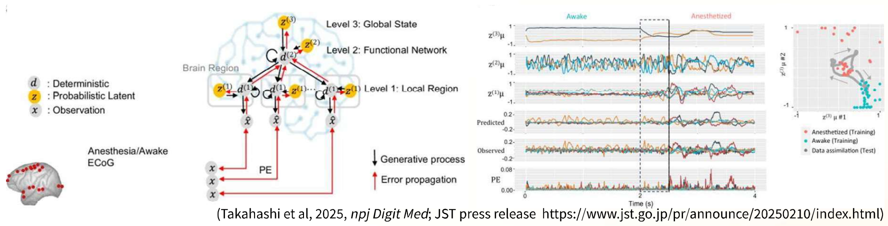
These findings represent an important step toward more advanced BMIs. If multiple intentions could be decoded simultaneously from brain activity, individuals who have difficulty moving or speaking could use prosthetic limbs more naturally and communicate their thoughts more freely.



A) Wireless cortical-wide ECoG system for free-moving primates B) Decoder architecture C) Cortical association areas contribute to multimodal decoding. (Komatsu et al, 2023, *Proc 10th Int BCI Meeting*)

Digital Twin Brain Simulator

We are developing methods to estimate brain network structure from cortical electrophysiological signals and to simulate neural activity based on these estimates. In a collaborative study with Dr. Yuichi Yamashita (National Center of Neurology and Psychiatry) under Moonshot Goal 3, we created a new digital twin brain simulator that performs real-time simulations of cortical activity in nonhuman primates.



(Takahashi et al, 2025, *npj Digit Med*; JST press release https://www.jst.go.jp/pr/announce/20250210/index.html)

This simulator models latent neural states across multiple hierarchical levels of the brain and generates high-precision virtual cortical signals. Moreover, by using data assimilation techniques—updating latent-state estimates in real time based on prediction–observation discrepancies—it provides simulations that continuously reflect the brain's current functional state.

Using this model, we demonstrated the feasibility of conducting virtual drug-effect simulations and estimating functional neural networks underlying ECoG signals. These results highlight the potential of digital twin brain technologies for both basic neuroscience and brain–machine interface applications.

This research, which aims to elucidate individual-specific mechanisms of neural information processing in real time, holds strong potential for future applications in personalized medicine. Looking ahead, we plan to develop comprehensive models that integrate multiple sensory modalities—including exteroceptive signals (e.g., vision and audition), interoceptive signals (e.g., cardiac and respiratory sensations), and proprioceptive signals (e.g., joint position and muscle sense)—in addition to brain activity. By doing so, we aim to reproduce the altered information-processing dynamics characteristic of psychiatric and neurological disorders in a unified and biologically grounded manner.

Future Prospects

We have found that a single device can predict multiple intentions, offering a clue toward a next-generation BMI based on a new concept. By accumulating more data, we aim to develop a BMI that enables diverse intention-driven behaviors with electrodes placed in only part of the brain.

Misako Komatsu, Ph.D.

Specially Appointed Associate Professor, Institute of Integrated Research, Institute of Science Tokyo

After completing her B.S. in Physics at Tokyo Metropolitan University, she obtained her Ph.D. in Science from Tokyo Institute of Technology. She subsequently worked as a Research Associate and Researcher at RIKEN, where she conducted studies using neural networks and electrophysiology. She is currently a Specially Appointed Associate Professor at the Institute of Innovative Research, Institute of Science Tokyo. She has developed large-scale cortical ECoG recording techniques in marmosets and aims to elucidate large-scale information processing mechanisms in the primate brain.

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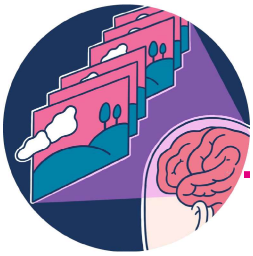
IoB Core Technology

Moonshot Research and Development Program Goal 1 Kanai Project



Liberation from the constraints of body and mind through artificial neural connections

Yukio Nishimura, Ph.D. Project leader, Neural Prosthetics Project, Tokyo Metropolitan Institute of Medical Science

Overview

Neurological disorders such as stroke, spinal cord injury, and amyotrophic lateral sclerosis (ALS) cause paralysis of voluntary movement and loss of somatosensation due to disrupted neural pathways connecting the brain and body. Central nervous system disorders are also frequently accompanied by depressive symptoms, which further hinder functional recovery. By enabling individuals to overcome these physical and psychological constraints and improving the quality of life (QoL) of patients with central nervous system injuries, we can expand their opportunities for participation and contribution in society. This, in turn, opens the door to significant new possibilities for emerging markets.

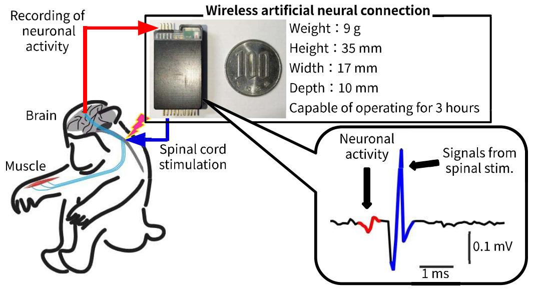
In this research and development project, we aim to create an AI-assisted brain–machine interface (BMI)–based artificial neural connection system that enables the liberation of both the body and mind in individuals with central nervous system disorders. Specifically, the project comprises: (1) development of technologies for writing information into the brain and spinal cord; (2) restoration of motor function for paralysis; (3) expansion of somatosensory capabilities; (4) induction of artificial emotions; and (5) development of neural communication technologies.

Through these integrated research efforts, we seek to establish a technological foundation that allows patients with central nervous system injuries to be freed within cyber-physical spaces and, ultimately, to gain the ability to flexibly control their own bodies and minds in real-world environments through AI-assisted BMI–mediated artificial neural connections. The feasibility and effectiveness of these technologies will be demonstrated using macaque models.

Development of Artificial Neural Connections Enabling Information Writing to the Brain

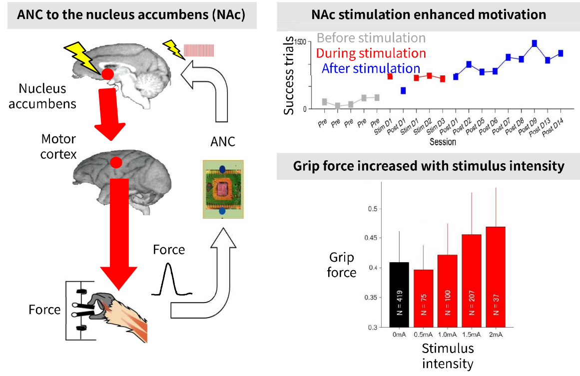
We developed a compact computer chip capable of detecting neural and muscular activity signals and delivering electrical stimulation, together with PC software that wirelessly controls the behavior of the chip. We then validated the operation of this system in macaque monkeys.

A portable, wireless artificial neural connection system that can record neuronal activity and deliver electrical stimulation



Augmenting Motivational Drive for Motor Behavior via Artificial Neural Connection

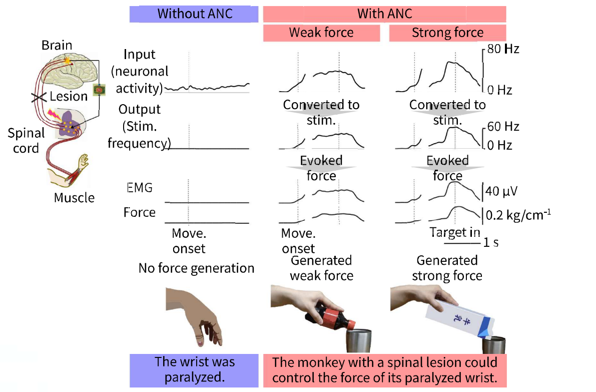
During a grasping task in animals, artificial neural connection (ANC) to the nucleus accumbens (NAc) triggered by grip-force signals enhanced motivation to perform the task and yielded stimulation-intensity-dependent improvements in grip force performance.



Restoration of Physical Motor Function in Motor Paralysis via Artificial Neural Connections

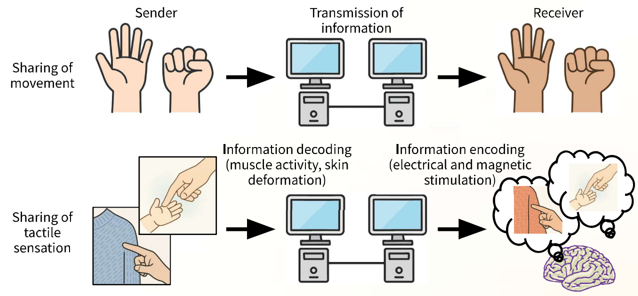
Using a rack-mounted artificial neural connection (ANC) system, a spinal cord injury model monkey was able to voluntarily modulate the magnitude of its neural activity and regained the ability to control force at the paralyzed wrist joint.

By applying an ANC that converts the neuronal activity into spinal stimulation in real time, the monkey with a spinal lesion was able to adjust the force of its paralyzed wrist to the required level.



Development of Neural Communication Technology Between Two Individuals

We are developing technologies that enable real-time sharing of motor and sensory information between two individuals—such as human-to-human or animal-to-human—by transmitting biological and neural signals over computer networks. We successfully transferred and reproduced hand movements via an intranet-based communication system. In addition, we have developed methods for transmitting various types of tactile sensations.



Future Prospects

- Development of an artificial neural connection system that simultaneously restores motor and somatosensory functions
- Remote artificial neural connection rehabilitation between therapists and patients with motor paralysis
- Functional enhancement through interspecies artificial neural connections
- Uploading and downloading brain states

Yukio Nishimura, Ph.D.

Project Leader, Neural Prosthetics Project,

Tokyo Metropolitan Institute of Medical Science

<Concurrent Appointments>

Visiting Professor, Department of Medical Genomics, Graduate School of Frontier Sciences, The University of Tokyo

Visiting Professor, Graduate School of Medical and Dental Sciences, Niigata University

<Awards>

2023 Tokyo Metropolitan Bureau of Social Welfare and Public Health Director's Award (Invention Category)

2024 Tsukahara Nakaakira Memorial Award

Toshiki Tazoe, Ph.D.
Associate Investigator, Neural Prosthetics Project, TMiMS

Osamu Yokoyama, Ph.D.
Assistant Investigator, Neural Prosthetics Project, TMiMS

Michiaki Suzuki, Ph.D.
Assistant Investigator, Neural Prosthetics Project, TMiMS

Masafumi Nejime, Ph.D.
Junior Investigator, Neural Prosthetics Project, TMiMS

Kei Obara, Ph.D.
Junior Investigator, Neural Prosthetics Project, TMiMS

Internet of Brains

国立研究開発法人科学技術振興機構ムーンショット型研究開発事業／株式会社国際電気通信基礎技術研究所
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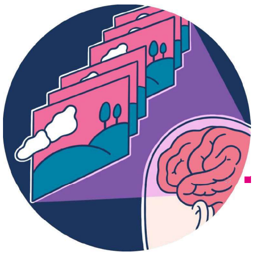


Technological Foundation for Transmitting Neural Activity Information Between Individuals and Information Transmission

Professor Hiroaki Wake Department of Multicellular Circuit Dynamics National Institute for Physiological Sciences National Institutes of Natural Sciences

Overview

If technologies enabling the extraction of learned and stored information from one brain and its transfer to another could be developed, the “information transmission” portrayed in science fiction would become reality. Achieving this, however, requires a causal understanding of how local neural circuits encode information through cell-level spatiotemporal activity patterns. Such learning-related neural dynamics form the basis of cognition and memory, and are deeply implicated in brain disorders, including neurodevelopmental and psychiatric conditions.

Recent advances in optogenetics and in vivo imaging have begun to elucidate the minimal neuronal ensembles and connectivity motifs capable of artificially inducing sensory percepts [Dalgleish et al., 2020; Carrillo-Reid et al., 2019; Marshel et al., 2019]. Nonetheless, the field lacks methods for artificially generating the spatiotemporal activity patterns of neuronal populations themselves, representing a major unexplored frontier in understanding the principles of learning and memory.

In this study, we will utilize holographic microscopy to simultaneously record and manipulate single-cell activity. By extracting learning-related neural dynamics and reproducing them in naïve circuits, we aim to causally test the relationship between circuit-level plasticity and behavior. Furthermore, by integrating glial manipulation—including astrocytes—we will investigate how coordinated temporal sequences of activity across neurons and glia support flexible perceptual learning.

Research: Information Transmission Content (Left Column) and Research Approach (Right Column)

Temporal activity of diverse learning-related neurons for information transmission

Results : Diverse neural responses in the barrel cortex encode learning-related information

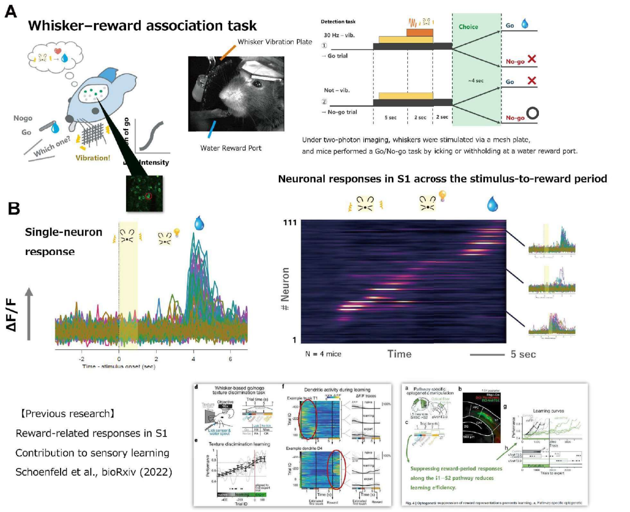


Fig1. A) Schematic of the whisker-reward association task under two-photon microscopy. B) Left: Example single-neuron Ca^{2+} activity and population response map. Task-related and decision-critical neurons exist in S1 barrel cortex, and manipulating them affects learning and behavior, indicating these circuits are essential for task performance.

Findings on learning-correlated astrocytic activity that may facilitate information transmission

Results : Astrocyte and neuronal activity correlated with learning rate increase

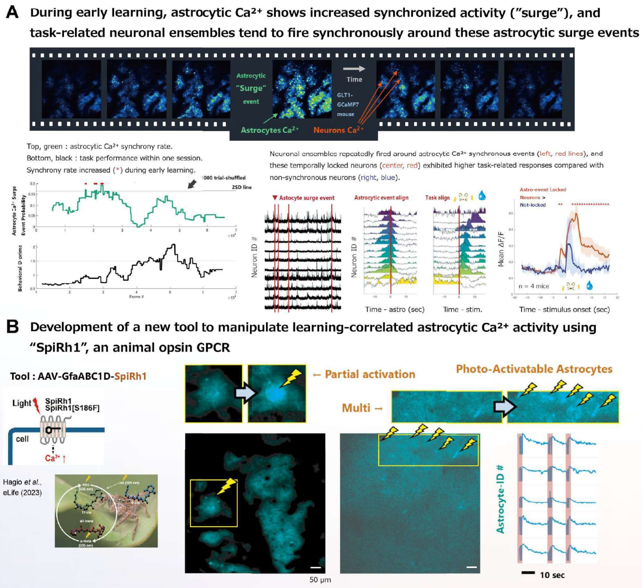
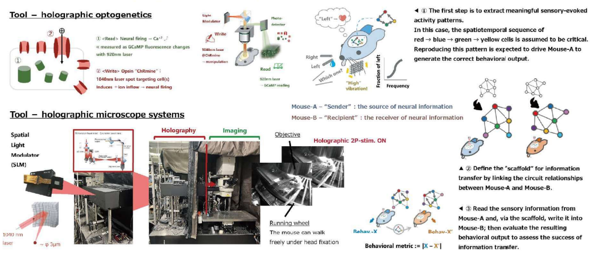


Fig2. A) Top: Simultaneous astrocyte–neuron Ca^{2+} imaging in GLT1-GCaMP mice. Astrocytic surge events induce large-scale, dynamic changes across the field of view. Bottom: During early learning, surge event rates increased when performance first reached threshold (d-prime > 1.5). Neurons phase-locked to surge events carried higher task-related information than non-locked neurons. B) Astrocytic Ca^{2+} activity was optogenetically driven by expressing an animal opsin GPCR in astrocytes and stimulating single or multiple cells using two-photon holographic stimulation.

Information-transfer project using a holographic microscopy system

Highlights : Holographic microscopy-based information transfer between mice



Methods : Information-transfer protocol | ROI selection and linking circuits across mice

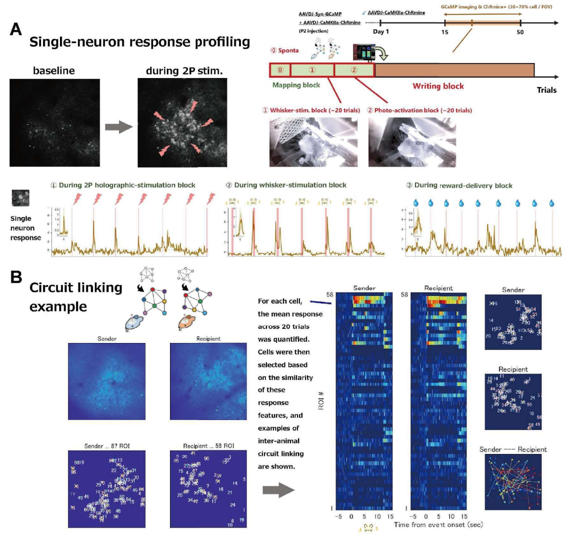


Fig3. A) In preparation for information transfer, barrel cortex neurons within the two-photon imaging field were labeled for light responsiveness using blocks that systematically stimulated all cells, and for whisker-evoked responses using blocks with passive sensory input. B) Based on the time-series features of these responses, corresponding neurons were linked across two animals.

Results : Information-transfer | compressed sender signals tended to shift behavior

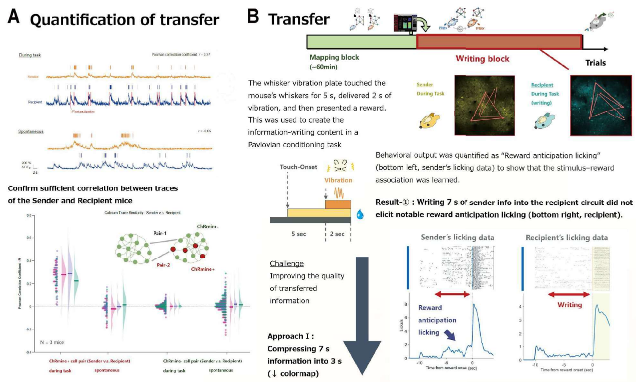
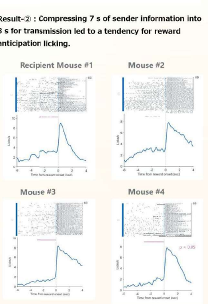


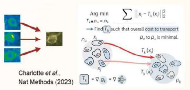
Fig4. A) Top: For quantifying information transfer accuracy, correlation coefficients between the sender trace (orange) and recipient trace (blue) are compared. Bottom: Distribution of correlation coefficients for photoactivatable cells (ChRmine+). Sufficient correlation is achieved during the transfer session. B) Schematic of the transfer protocol and reward-anticipatory lick raster. Each dot shows a tongue touch to the reward port. Blue line: average lick-rate. After learning, licking before reward increases significantly vs. baseline.



Discussion : Improving the amount and quality of transferred information

We will compare multiple transfer protocols and quantify the resulting behavioral changes.

- Enhance transfer by activating astrocytic activity essential for learning
- Enhance transfer by temporally compressing the information
- Enhance transfer by condensing multi-cell information into a single cell
- + more ...



Future Prospects

By enabling information transmission, we aim to expand brain function using organoids and animal brains!

Hiroaki Wake
Professor NIPS

Yuta Tanisumi
Research Fellow, NIPS

Noriaki Fukatsu
Research Fellow, NIPS

Internet of Brains

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IoB Minimally Invasive Technology

Intravascular Devices for Long-Term, High-Fidelity Neural Monitoring

Institute of Scientific and Industrial Research, the University of Osaka: Tsuyoshi Sekitani (SPM), Takafumi Uemura (PI), Teppei Araki, Toshikazu Nezu,

Graduate School of Medicine, the University of Osaka : Hajime Nakamura (PI), Takufumi Yanagisawa (SPM)

Moonshot Research and Development Program Goal 1 Kanai Project

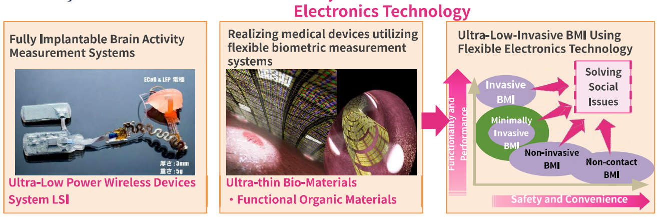
IoB Minimally Invasive

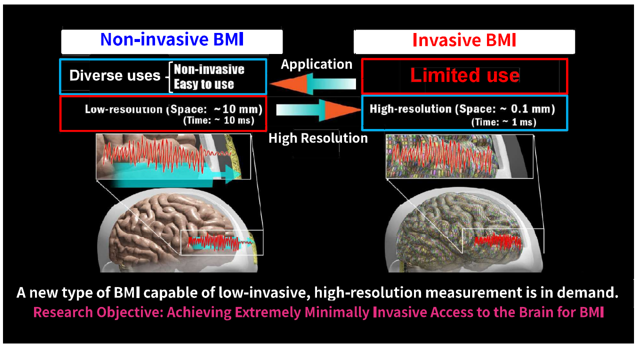
Overview

We are currently developing an intravascular brain–machine interface (intravascular BMI) that uses an ultra-thin film electrode device designed to be placed within cerebral veins near the cortical surface. The device can be inserted into intracranial veins using catheter-based endovascular procedures, enabling high-precision recording and stimulation of brain activity through the vessel wall. Positioned between invasive ECoG electrodes that require craniotomy and non-invasive scalp EEG, this technology represents a new platform for neural measurement and intervention that achieves both long-term signal stability and safety. Looking ahead, we envision it evolving into a next-generation IoB technology capable of enhancing human physical, cognitive, and sensory functions.

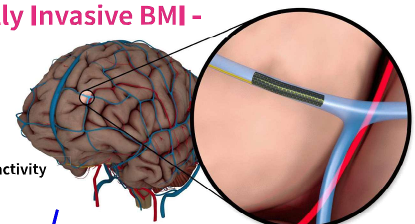
R&D 5: Realization of Minimally Invasive BMI

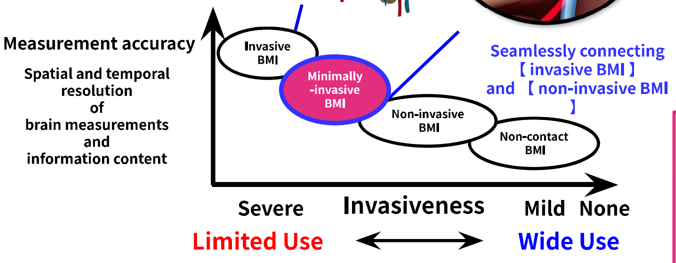
Development of an Intravascular EEG Recording System and an Ultra-Fine-Diameter Delivery Device Based on Ultra-Thin-Film Flexible Electronics Technology





- Extremely Minimally Invasive BMI -





Two Devices for a Minimally Invasive BMI System

- Minimally Invasive BMI System Utilizing an Ultra-Fine, Flexible Intravascular Implant Device
- Intravascular EEG Measurement Device Serving as a BMI Signal Acquisition Platform

Research Structure

Ultra-low invasiveness through thin-film electronics

Ultra-thin (1 μm), lightweight, flexible, stretchable sensors and integrated circuits (past achievements)

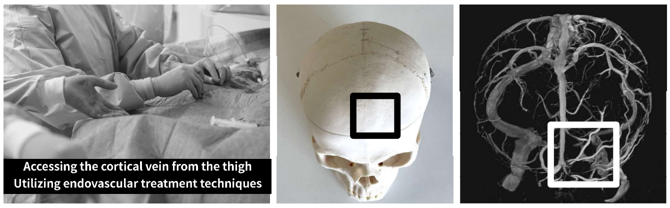
Micro-Bioelectric Potential Measurement Device

- Certified as a Medical Device -

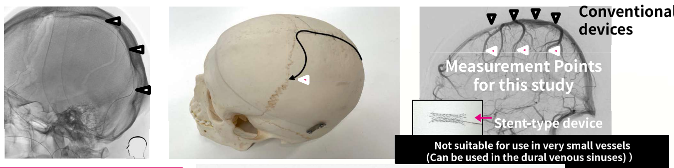
Demonstrates a proven track record in biocompatibility, measurement accuracy, and other aspects.

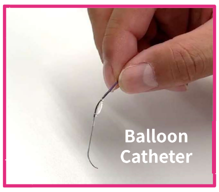
Access to the cortical veins running along the surface of the cerebrum is extremely difficult

Small vessel diameter, thin and fragile vessel walls, marked tortuosity



Because cortical veins are not protected by the dura mater, they are structurally vulnerable. However, their close proximity to the cortical surface makes them a promising target for minimally invasive intravascular devices capable of acquiring high-quality EEG signals.

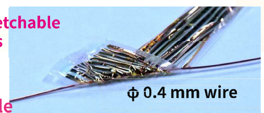




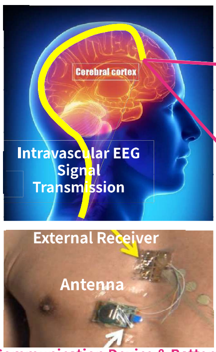
A sensor-equipped delivery device capable of transporting BMI to complex-shaped cerebral surface veins

- Guiding wire (φ<0.36mm)
- Guiding Catheter (φ<1mm)

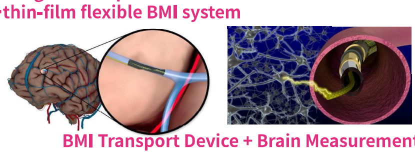
Ultra-thin, Flexible, Stretchable Electronics Applications



Long-term implantable thin-film flexible BMI system



Communication Device & Battery



BMI Transport Device + Brain Measurement

Enables extremely minimally invasive measurements and electrical stimulation

Current R&D Activities

Advancing Research and Development for High-Precision Intravascular EEG Measurement

- Development of Biocompatible Electrodes and Ultra-Thin-Film Sensor Probes
- Development of Intravascular Micro-Biological Signal Acquisition and Transmission Technologies

Internet of Brains

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IoB Minimally Invasive

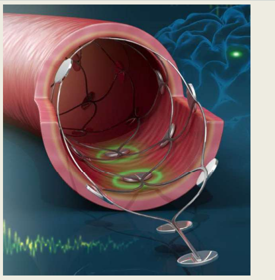
Moonshot Research and Development Program Goal 1 Kanai Project

Brain–Machine Interfaces

David B. Grayden, Clifford Chair of Neural Engineering, University of Melbourne, Australia

Overview

Our groundbreaking brain-computer interface (BCI) research is paving the way for revolutionary advancements in human-machine interaction. We are exploring innovative methods to decode visual information from the brain using endovascular recordings near the visual cortex, potentially enabling object classification through brain signals alone. Our studies also demonstrate that electrical stimulation of the brain through blood vessels can be achieved. Furthermore, our optical BCI system using fluorescent imaging can measure the activities of individual neurons with real-time decoding. Simultaneously, we are harnessing large datasets and machine learning to enhance BCI accuracy and reliability, bringing us closer to practical, home-based applications. These cutting-edge projects promise to transform how we interact with technology.



Endovascular neural interface

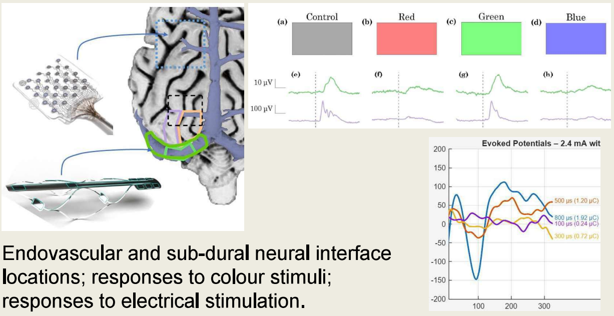
Endovascular Recording and Simulation

Endovascular recording of visual responses

Six sheep were implanted with endovascular electrodes near the visual cortex. Visual stimuli were presented with different colours and with controlled semantic classes: sheep, dog, and flowers, with varying primary visual features: background, image scale, and face vs. full body. A temporal convolutional network was applied to learn to classify the neural recordings. Moderate success was achieved for discriminating colours, and dog and dandelion flower images, while sheep images were not clearly distinguished from flower images. The neural signal can be differentiated when dividing into closeup images of dog or sheep faces vs. full-body images.

Endovascular stimulation of the cerebellum

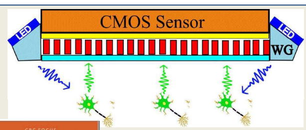
Endovascular electrodes were manufactured and underwent *in vitro* testing to characterise their electrochemical properties, including impedance analysis, charge storage capacity, and voltage transient measurements. Surface characterization using atomic force microscopy (AFM) and scanning electron microscopy (SEM) was conducted. Results indicated an optimized roughness profile, maximizing charge injection efficiency. Endovascular electrodes were implanted near the cerebellum in sheep along with sub-dural electrodes in the motor cortex region to record cortical evoked potentials elicited by the stimulating the endovascular electrodes. There were prominent responses at approx. 100 ms post-stimulation, suggesting cerebellum activation.

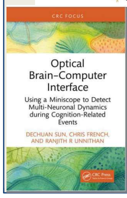


Endovascular and sub-dural neural interface locations; responses to colour stimuli; responses to electrical stimulation.

Optical Brain-Computer Interface

In this project, we aim to develop an optical BCI and associated rapid real-time decoding of the optical signals. We have extensive experience with intracranial neuronal fluorescent imaging with miniaturised fluorescent microscopes. We have found >500 neurons can be tracked for >1 year with minimal signal degradation and very high information content. Notably there is no direct contact with neurons, avoiding the tissue damage and signal impairment occurring with penetrating electrodes. Fluorescent signal in brain cells is achieved by using an innocuous viral vector to express fluorescent proteins and these techniques have been used in non-human primates. A key to implementing this technology as a BCI is the need for rapid real-time decoding of the optical signals. We have recently developed a real-time decoder using machine learning techniques that achieves an extremely high rate of decoding (~200 frames/second).





Conceptual prototype: CMOS camera sensor with filters (yellow), illumination system (blue) and lenses (red)

AI and Machine Learning for BCI Decoding

A deep neural network with an encoder and a decoder-only Large Language Model (LLM) is investigated for subject-specific visual semantic decoding. The encoder maps the ECoG data into high-level neural representations, while the decoder interprets the representations into natural language. The experimental work has focused on exploration of different deep learning algorithm as the encoder for open-vocabulary neural decoding. We employ three encoders, each with a well-known ability to capture sequential dependencies: (1) a convolutional neural network with 1-dimensional kernels (1D CNN) applied to the time domain; (2) a customized transformer that jointly attends to both spatial and temporal dimensions; and (3) a simplified transformer with temporal causal attention.

Future Prospects

Full closed-loop BCI using endovascular electrodes that both record and stimulate to provide human-machine and human-human communication.

High density, minimally invasive neural recording using optical BCI for complex human-machine interactions.

David B. Grayden

Clifford Chair of Neural Engineering, University of Melbourne, Australia

Department of Biomedical Engineering, Faculty of Engineering & Information Technology and the Graeme Clark Institute for Biomedical Engineering. Co-Director of the Victorian Medtech Skills and Devices Hub and Director of the ARC Training Centre in Cognitive Computing for Medical Technologies. Main research interests are in understanding how the brain processes information, how best to present information to the brain using medical bionics, such as the bionic ear and bionic eye, and how to record information from the brain, such as for brain-machine interfaces. Teaches BioDesign Innovation in collaboration with the Melbourne Business School. Co-Director of Biodesign Australia.

Project Faculty: Sam John, Chris French, Takufumi Yanagisawa
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Research Assistants: Huakun Xin, Luke Weston
Student: Qi Meng
Collaborators: Joseph West, Ranjith Unnithan, Anthony Burkitt,
Yi-De (Frank) Tai, Bryce Widdicombe, Jingyang Liu, Martin Spencer,
Jelle H. M. van der Eerden, Po-Chen Liu

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Moonshot Research and Development Program Goal 1 Kanai Project

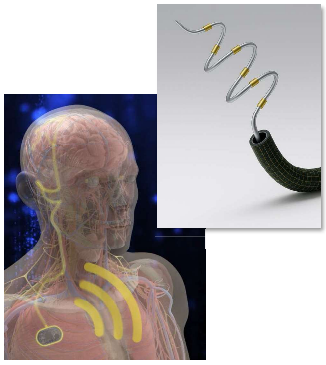
IoB Minimally Invasive

Development of an Extremely Minimally Invasive Intravascular Brain-Machine Interface (BMI) System

Associate Professor, Department of Neurosurgery, The University of Osaka Graduate School of Medicine
Hajime Nakamura

Overview

Realizing AI-assisted BMI-CA requires an interface that connects the brain and external systems bidirectionally. Based on the method used, these interfaces are categorized into "invasive BMI" and "non-invasive BMI." Invasive BMI employs surgical techniques to implant electrodes within the skull, enabling the utilization of brainwave signals obtained from these electrodes for BMI. This approach allows for the processing of large amounts of information with low latency. However, challenges existed for human application due to the necessity of craniotomy and high costs. This research and development project aims to develop an "**extremely minimally invasive intravascular BMI system**." This system utilizes flexible, thin-diameter intravascular electrodes that can be guided into cerebral blood vessels to detect highly accurate brainwave signals with minimal invasiveness for BMI application. This project is being pursued in close collaboration with **Takashi Yanagisawa, SPM (R&D Project 3-2-2), Takeshi Sekiya, SPM (R&D Project 5-1-1), and Takafumi Uemura, PI (R&D Project 5-1-3)**. Previous research results and future prospects are described below.



1. Can brain waves be measured from inside blood vessels?

There is no existing technology that detects brainwave signals from cortical veins (CV) running on the brain's surface and utilizes them for BMI, and its usefulness has not been proven. Therefore, we first decided to verify whether it is possible to detect brainwave signals using intravascular electrodes placed in CVs, using large animals such as pigs and sheep. The brains of large animals are significantly smaller than those of humans, and the vessels running along their surfaces are also extremely small (Figure 1). Consequently, we decided to use the large animal hybrid operating room at the Fukushima Medical Device Development Support Center, which is equipped with cerebral angiography equipment used in actual surgeries. At this facility, we guided a microcatheter from a pig's femoral vein to a cerebral surface vein (diameter 0.8 mm). Through this catheter, we placed our developed ultra-fine intravascular electrode and performed EEG measurements. To verify the accuracy of EEG measurement, we performed a craniotomy on the pig using the same invasive BMI method and compared the measured EEG signals with those obtained from sheet electrodes placed on the brain surface (Figure 2). The results of this experiment demonstrated that somatosensory evoked potentials (SEPs) could be measured with higher accuracy using the intravascular electrode than with the sheet electrode, indicating the usefulness of intravascular EEG measurement from the CV (Figure 3). Furthermore, long-term stability was confirmed by keeping pigs for extended periods with intravascular electrodes placed in the superior sagittal sinus (SSS), an intracranial vessel with a maximum diameter of approximately 2-3 mm. Successful EEG measurement was achieved even on day 49 post-implantation (the longest duration) (Figure 4).

These results suggest that an ultra-low-invasive intravascular BMI system targeting cerebral veins has the potential to provide highly accurate EEG signals over long periods with less invasiveness compared to invasive BMI using sheet electrodes.

Figure 1

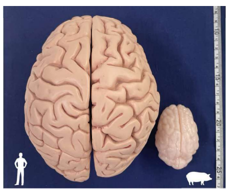


Figure 2

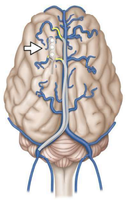


Figure 3

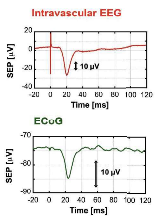
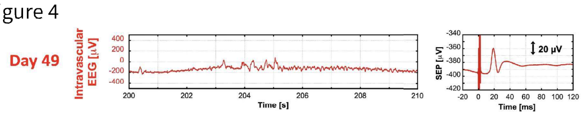


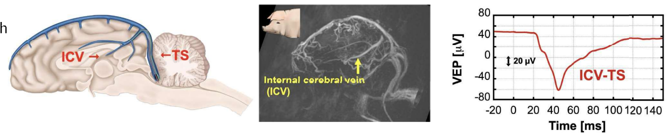
Figure 4



2. The Potential of Extremely Minimally Invasive Intravascular BMI Systems

The extremely minimally invasive intravascular BMI system is a thin and flexible device that could be placed in the internal cerebral vein (ICV), a vein running deep within the brain (Figure 5). The ICV runs near the occipital lobe and thalamus. Using an intravascular electrode placed in the ICV, we succeeded for the first time worldwide in detecting visual evoked potentials (VEP). Our ultra-thin intravascular electrodes enable measurement of brainwave signals from regions previously inaccessible with conventional methods, suggesting potential applications beyond BMI, such as epileptic focus localization and interventions for higher brain dysfunction.

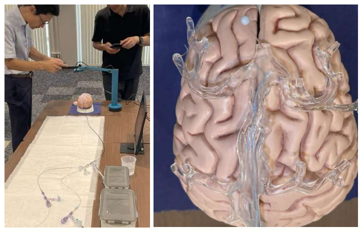
Figure 5



3. Simulation System Using 3D Printers

Experiments using pigs demonstrated the utility of the minimally invasive intravascular BMI system. However, to attempt application in humans, various device properties—such as size, flexibility, lubricity, and visibility—must be evaluated using human vascular models. In parallel with the pig experiments, we also performed device placement simulations using a 3D cerebral venous model created from human cerebral angiography data (Figure 6).

Figure 6



4. Intravascular CA Development Center@Osaka University

With support from the moonshot-type research and development initiative, the latest cerebral angiography system (Siemens ARTIS icono) was introduced to the animal research facility at Osaka University's Faculty of Medicine in fiscal year 2025. Utilizing this system is expected to accelerate the development of a extremely minimally invasive intravascular BMI system and bring us closer to its implementation in society.

Future Prospects

This study demonstrated the utility and future potential of the minimally invasive intravascular BMI system. Moving forward, we plan to verify the device's long-term safety while preparing for preclinical trials. We have also established a placement simulation system using human 3D models and will strive to enhance the safety of placement procedures. We are fully committed to realizing the societal implementation of this system in collaboration with the IoB Minimally Invasive Team.

Hajime Nakamura

Associate Professor, Department of Neurosurgery, The University of Osaka Graduate School of Medicine

Vice Director, Stroke Center, Osaka University Hospital

I serve as the head of the Cerebrovascular Disease Treatment Team at Osaka University Hospital. I strive to develop gentle yet effective treatment strategies for patients by combining craniotomy with endovascular procedures. In this research project, I will dedicate myself to developing an ultra-minimally invasive endovascular BMI system, maximizing the utilization of neurosurgical techniques.

Haruhiko Kishima

Professor, Department of Neurosurgery, Graduate School of Medicine, Osaka University

Tomohiko Ozaki

Assistant Professor, Department of Neurosurgery, Graduate School of Medicine, Osaka University

Masatoshi Takagaki

Assistant Professor, Department of Neurosurgery, Graduate School of Medicine, Osaka University

Takaki Matsumura, Yuji Naramoto, Kunimasa Teranishi, Hiroki Yamazaki, Hitomi Kuramoto, and others

Osaka University Graduate School of Medicine Department of Neurosurgery Cerebrovascular Disease Group Staff Physicians

Internet of Brains

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Moonshot Research and Development Program Goal 1 Kanai Project

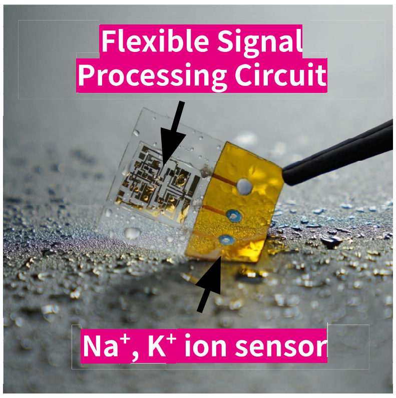
IoB Minimally Invasive

IoB Minimally Invasive Technology
Development of Wearable Devices for Long-Term Measurement

Professor, SANKEN, The University of Osaka Takafumi Uemura

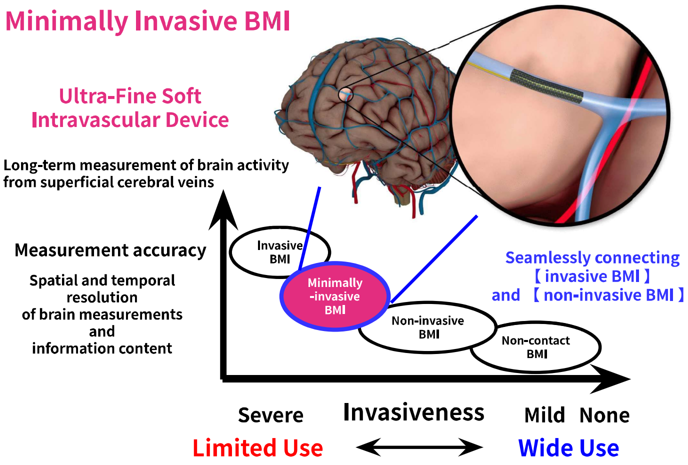
Overview

In the development of minimally invasive IoB technologies, we are creating a new BMI technologies that achieves both high precision and safety - goals difficult to realize with existing technologies. This involves developing BMI technologies that are more advanced than invasive approaches, which requires surgical procedures, and non-invasive approaches, which capture information from the body's surface, with minimal invasiveness. Specifically, we are developing technology to acquire EEG signals from within cerebral veins using intravascular treatment techniques involving catheters, a form of minimally invasive therapy. This research involves fundamental studies for the long-term use of chemical sensors to **realize wearable sensors capable of continuously measuring bio-derived chemical quantities such as ions and molecules over extended periods**. The goal is to quantitatively measure ions and various molecules secreted into the blood or outside the body as a result of human physiological responses. **By simultaneously achieving the measurement of physical quantities such as brain waves and the composition of secretions from the body, we aim to realize the expansion of physical, cognitive, and perceptual abilities at a more advanced level.**



IoB Minimally Invasive Technology

Minimally Invasive BMI

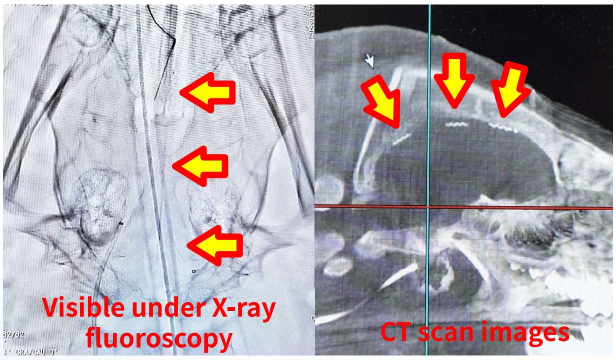


Two Devices for an Ultra-Minimally Invasive BMI System

- An 【Minimally Invasive BMI System】 using an Ultra-Fine, Flexible Intravascular Device
- An 【Intravascular EEG Measurement Device】 Functioning as a BMI Transporter

Utilization of Flexible Electronics Technology

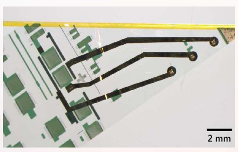
Diameter: 1 mm
Intravascular electrode



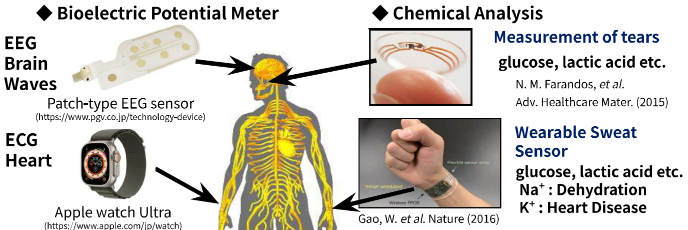
A spiral-shaped electrode is placed in the cerebral venous vessels, enabling electroencephalogram (EEG) measurement.

Future Prospects

We have achieved EEG measurement by placing flexible electrodes within cerebral venous vessels. Moving forward, we aim not only to measure EEG but also to realize quantitative chemical measurements, including electrolytes. Additionally, we plan to integrate thin-film flexible electronic circuits into the vessels, as shown in the right figure, to achieve high-quality biological signal measurement.



Current State of Wearable Devices



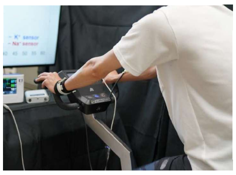
Physical measurement sensors
Numerous products exist
Bioelectrodes and optical sensors operate with long-term stability.

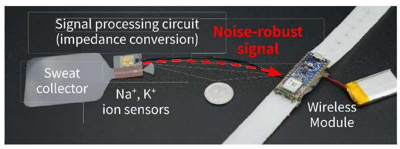
Metabolites (chemical substances) are useful analytical targets
Ex. Blood and Urine Analysis in Regular Health Checkups
Challenges for Wearables:
Long-Term Stability of Chemical and Biosensors

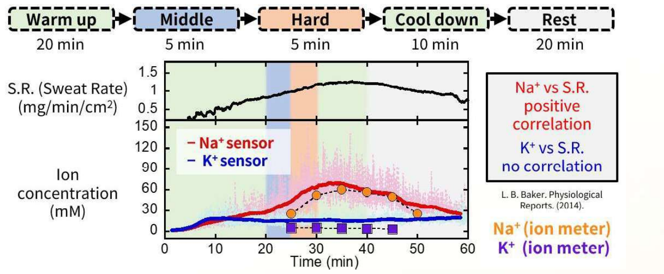
【Goal】 Develop stable biosensors for use in intravascular measurement

Continuous measurement of electrolyte concentration during exercise sweating

Wireless electrolyte measurement during exercise sweating



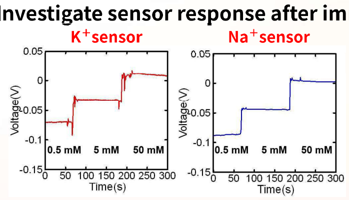




Successful continuous measurement of electrolyte concentrations during exercise sweating

Toward the Measurement of Chemical Quantities in Blood

Investigate sensor response after immersion in blood (15 minutes)



Antithrombotic polymer (inhibits protein adsorption) coating confirmed sensor response maintenance

Takafumi Uemura

Professor, SANKEN, The University of Osaka

Associate Professor, Department of Advanced Thin-Film Functional Properties

Graduate School of Information Science and Technology, Department of Information Systems Engineering (Concurrent)

https://researchmap.jp/Takafumi_Uemura : QR code

Email : uemura-t@sanken.osaka-u.ac.jp

Internet of Brains

国立研究開発法人科学技術振興機構ムーンショット型研究開発事業／株式会社国際電気通信基礎技術研究所

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Moonshot Research and Development Program Goal 1 Kanai Project

IoB Fundamental Technologies

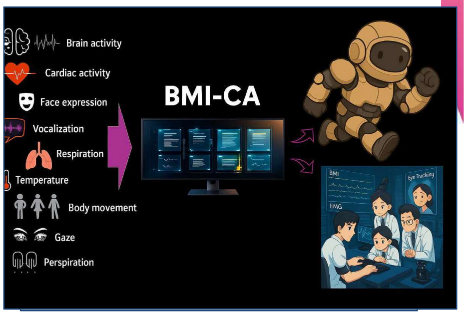
Development of a New Interface for Cybernetic Avatar (CA) Operation

~ A Platform for Integrating Multi-modal Information

Kan Akutsu Team Leader, ARAYA Inc.

Overview

Brain-Machine Interfaces (BMIs), which connect the brain to external devices, are anticipated to be used as interfaces for operating Cybernetic Avatars (CAs). However, an optimal interface that is accessible to everyone does not yet exist. This research aims to identify the optimal interface for CA operation by integrating and combining multiple types of sensory information, such as EEG (brainwaves) and EMG (muscle signals), with a view toward practical implementation in society. Handling different types of biological data like EEG and EMG together is challenging, and no general-purpose solution existed. Therefore, we built a "BMI-CA Platform" that standardizes multiple bio-signals and can be operated entirely via a GUI, enabling even non-experts to develop interfaces for avatar operation.



The BMI-CA Platform

The BMI-CA Platform is software that enables easy, synchronized acquisition of diverse bio-signals (e.g., EEG, EMG), along with real-time analysis and visualization. It provides a flexible multi-modal analysis environment for researchers and an intuitive operational experience for general users, targeting a wide range of applications from medicine and education to entertainment.

Features

✔ Diverse Signal Processing: Synchronized acquisition, real-time analysis, and visualization of EEG, EMG, and eye-tracking data. ✔ User-Adaptive Flexibility: Simple GUI blocks for users unfamiliar with programming, alongside advanced customization options for experts.

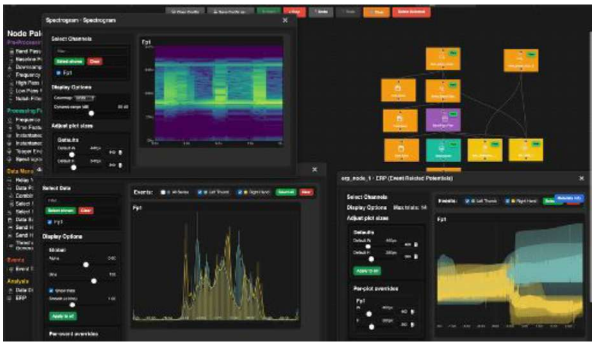
✔ Device-Agnostic Standardization: Improves development efficiency by standardizing data formats and calibration methods across different sensors.

✔ Command Conversion: Easily translates analysis results into control commands for virtual environments or physical robots.

✔ Cross-Platform Support: Docker-based system compatible with Linux, Windows, and Mac, simplifying environment setup.

Future Outlook

We plan to make this platform open-source, further enhancing support for commercial sensors, real-time processing, and machine learning integration. Our future goal is to develop this into a "BMI infrastructure accessible to everyone, like the internet," accelerating global joint research, industrial applications, and the real-world deployment of new operational experiences.



BMI-CA Platform analysis screen

Various Use Cases

🏭 Industry

The platform can be applied as a next-generation controller for operating robots or game characters by integrating multiple bio-signals. It is expected to support a wide range of targets, from small robots to large construction machinery, enabling intuitive control that naturally reflects the user's intent. Furthermore, as a common infrastructure for BMI-based application development, it is expected to be used in entertainment, such as for controlling new game characters.

🩺 Healthcare

The platform is expected to serve as a foundation for continuously monitoring health status, concentration levels, and stress by visualizing brain activity and physical conditions in real-time. This not only supports daily self-care and performance management but can also be utilized as an auxiliary interface in rehabilitation and welfare, holding promise for applications in the medical and welfare fields.

Joint Research with Dubai Future Labs

The "Internet of Brains" (IoB) project, in collaboration with Dubai Future Labs (DFL) operated by the Dubai Future Foundation (DFF), has initiated joint R&D on next-generation BMI technology. This technology will allow people to freely control robots and avatars using their own EEG (electrical signals from the brain) and EMG (electrical signals from muscles).

Site visit in Japan, May 2025

Our partnership with DFL is a strategic move to dramatically accelerate the real-world implementation of our advanced technology. DFL, with strong support from the Dubai government, is one of the world's leading organizations in rapidly promoting the demonstration and societal implementation of future technologies, utilizing the entire city as a "Living Lab." Dubai's diverse environment, where people from over 200 nationalities coexist, provides an unparalleled and ideal testbed for verifying the global acceptance of our technology. Through this partnership, we aim to go beyond technological development to validate social and cultural acceptance, deploying truly valuable research outcomes to the world.

Future Prospects

By developing a platform capable of integrating multiple modalities, we have successfully lowered the barrier for multi-modal analysis and application development. We will continue to update the platform to integrate the various core technologies created within the IoB project. We will also expand its practical use cases—from research to application development in various fields and education—and evolve the platform by incorporating user feedback to ensure it becomes a vital tool for society used by many.

Kan Akutsu

Team Leader, MultiSense Foundation, ARAYA Inc.

After completing his Master's degree at the Graduate School of Information Science and Technology at the University of Tokyo in 2012, Kan Akutsu joined DeNA Co., Ltd., where he developed and planned multiple IP-based titles. He later joined ZEALS Co., Ltd. as a Product Owner, engaging in the development of general-purpose conversational robots. Currently, as the Team Leader of the MultiSense Foundation at ARAYA Inc., he serves as a Principal Investigator (PI) under Project Manager (PM) Kanai in the IoB project, advancing research on a common infrastructure for avatar operation using multi-modal bio-signals, including brain information.

Sarah Cosentino

Chief Researcher, MultiSense Foundation, ARAYA Inc.

Akihito Yoshida

Researcher, MultiSense Foundation, ARAYA Inc.

Yi-Chen Lin

Senior Researcher, MultiSense Foundation, ARAYA Inc.

Ángel Muñoz González

Chief Researcher, MultiSense Foundation, ARAYA Inc.

Ates Eren Dogus

MultiSense Foundation Product Development Manager, ARAYA Inc.

Keita Matsumoto

Construction Solutions Division Leader, ARAYA Inc.

Internet of Brains

国立研究開発法人科学技術振興機構ムーンショット型研究開発事業／株式会社国際電気通信基礎技術研究所

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Exploring the Future Society with Neurotech from Humanities and Social Sciences

“Internet of Brains”–Society

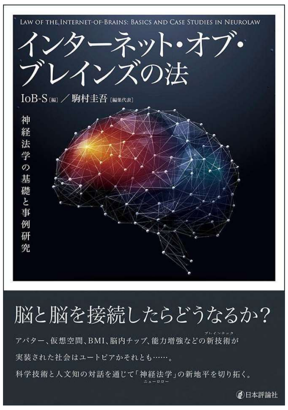
Keigo Komamura, Professor, Faculty of Law, Keio University.
Masatoshi Kokubo, Assistant Professor, Interfaculty Initiative in Information Studies Graduate School of Interdisciplinary Information Studies, The University of Tokyo.

Overview

The “Internet of Brains”-Society is a team composed primarily of legal scholars, ethicists, philosophers, and lawyers. We are examining what kind of relationship between the Internet of Brains (IoB) and individuals would be desirable when the society realized by IoB arrives.

Specifically, we are examining how to safeguard the values, rights, and freedoms we hold dear while ensuring the welfare brought by technology. Working backward from the vision of an ideal society, we are exploring what legal and ethical responses, policies, and systems will be necessary.

To this end, we are conducting research primarily within the new legal field of “neurolaw,” expanding our activities both domestically and internationally. We have also engaged in discussions informed by science fiction-inspired imagination and held repeated dialogues with the young people who will lead the next generation.



Law of the Internet of Brains: Basics and case studies in Neurolaw

At IoB-S, we have conducted research primarily with natural scientists and engineers participating in the Kanai Project, engaging in ongoing dialogue with natural scientists and physicians in the fields of neuroscience, cognitive science, and psychiatry. Specifically, by sharing the current state and future prospects of advancing neuroscience and technology research and development, we have examined the potential risks and benefits from a legal and ethical perspective, sometimes including bold predictions about the future, and also what systems and mechanisms are necessary to accelerate the research and development of new technologies while safeguarding the values, freedoms, and rights cherished in our society, thereby maximizing the welfare they bring, as we strive to achieve and realize the vision of the IoB-S.

The outcomes of this work were serialized over two years(2022-2023), in the renowned legal journal 『Law Seminar』. Subsequently, after multiple content updates, it was published as a single volume titled 『Law of the Internet of Brains: Basics and case studies in Neurolaw』 in 2025.

Additionally, Keigo Komamura organized roundtables titled “The Future of Multi-disciplinary Knowledge: Pioneering Human Potential,” and “How to Approach Future Challenges Beyond the Divide Between Humanities and Sciences”. These were published in the『Mita-Hyouron』a journal with a large readership in the business community. We also published the book 『Liberty 2.0』, which explores the relationship between cutting-edge technologies, including neurotechnology, and “freedom.”

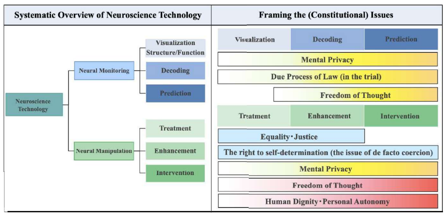
Through these initiatives, we communicated the importance and significance of engaging with the emerging field of “neurolaw”—still unfamiliar in Japan—to the research community while simultaneously producing numerous pioneering achievements in this area.

Furthermore, IoB-S members have disseminated information to diverse stakeholders beyond the research community by participating in newspaper interviews and writing web articles.

Research and opinion dissemination on the international stage

The International Neuroethics Society (INES) and the International Society for Public Law (ICON･S), as well as conferences, events, and joint research meetings held in various countries, have enabled us to actively disseminate research findings and opinions on the international stage. We have also established a significant presence within the global discourse.

Additionally, our members participate in the development of recommendation documents and guidelines being advanced by UNESCO, WHO, UNHRC, OECD, and IEEE, actively contributing opinions. We plan to further strengthen these activities going forward.



A Systematic Overview of Neuroscience Technologies and a List of Constitutional Issues
(Excerpted and partially modified from Kokubo, “The System of Neurolaw,” 2024)

Engagement with society

IoB-S has pursued effective ELSI discussions while valuing engagement with society alongside academic activities. Members have authored essays serialized on the official Ghost in the Shell global website and participated in events at the Setagaya Literature Museum, engaging with both the expectations and anxieties of the general public interested in SF- imagination and the world of SF. They have also spoken at events held at CIC Tokyo, fostering exchange and dialogue with companies and practitioners.

Furthermore, we organized events at the Keio University Doctoral Leading Program Summer Camp and held lectures at Keio High School for the next generation of young leaders. Through dialogue with those who will navigate a world where neurotechnology is widespread, we strive to provide information, foster shared awareness of issues, and cultivate talent capable of addressing ELSI and advancing scientific research.

Moving forward, we will continue to pursue ELSI research that transcends the confines of academic books, aiming instead for ELSI research that can play a role within society.

Future Prospects

In response to the rapid advancement of neuroscience technology implementation in society, various international organizations are accelerating efforts to establish rules specifically targeting the implementation of neuroscience technologies. Japan will actively participate in these efforts, aiming to reflect the perspectives and opinions of IoB-S in rule-making through proactive international engagement. Furthermore, to ensure society appropriately embraces neuroscience technologies with their significant potential and achieves a balance between risks and benefits, we will continue to actively pursue research, engage in dialogue with diverse stakeholders, and provide information.

Keigo Komamura
Professor, Faculty of Law, Keio University

Keigo Komamura: Born in Tokyo in 1960. Graduated from the Department of Law, Faculty of Law, Keio University. Served as Professor at Hakuoh University and Associate Professor at the Faculty of Law and Graduate School of Law, Keio University, and is currently Professor at the Faculty of Law, Keio University. Doctor of Juridical Science. Specializes in constitutional law. Member of the Advisory Committee for the Constitutional Amendment Research Project at Harvard University's Reischauer Institute. Author of works including The Modern Transformation of Constitutional Litigation (Nippon Hyoronsha), The Legal Theory of Journalism (Sagano Shoin), and Aspects of the Separation of Powers (Nanso-sha).

Masatoshi Kokubo
Assistant Professor, Interfaculty Initiative in Information Studies Graduate School of Interdisciplinary Information Studies, The University of Tokyo

Yoshinori Oshima
Attorney. Professor, Graduate School of Law, Senshu University

Ken Tsutsumibayashi
Professor and Dean of the Faculty of Law, Keio University

Satoshi Yokodaido
Professor, Graduate School of Law, Keio University

Kunifumi Saito
Associate Professor, Faculty of Policy Management, Keio University

Takayuki Matsuo
Attorney

Masahiko Sudo
Attorney

Satoshi Narihara
Associate Professor, Kyushu University Faculty of Law Department of Basic Legal Studies.

Tamami Fukushi
Professor, Faculty of Human Welfare, Tokyo Communication University

Tomoumi Nishimura
Associate Professor, Graduate School of Law, Kyushu University

Internet of Brains

国立研究開発法人科学技術振興機構ムーンショット型研究開発事業／株式会社国際電気通信基礎技術研究所
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IoB Fundamental Technologies

Moonshot Research and Development Program Goal 1 Kanai Project

Building Trust in Neurotechnology: Guidebook, Evidence book, & TMS Robot

Mitsuaki Takemi, Associate Professor, Graduate School of Advanced Science and Engineering, Hiroshima University.

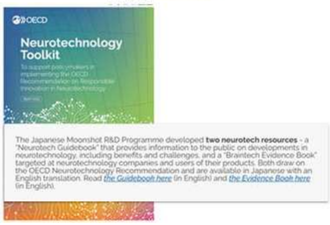
Overview

As consumer neurotechnology rapidly expands, three issues limit its responsible use: (1) limited literacy among users and developers, (2) fragmented scientific evidence, and (3) uncertainty about potential effects on the human body. This project addresses these issues through **knowledge sharing**, **evidence consolidation**, and **standardized physiological assessments**.

For knowledge sharing, we created the Neurotech Guidebook series. Vol.1 explains core concepts, major measurement and intervention methods, and common risks. Vol.2 provides a structured handbook for responsible development, covering legal requirements, safety, scientific validity, and information disclosure. For evidence consolidation, we conducted 12 systematic reviews on non-medical neurotechnology and published the results in the Evidence Book, Both the Guidebook and Evidence Book are cited in the OECD Neurotechnology Toolkit and are internationally referenced. Finally, for standardized physiological assessments, we developed an automated TMS robot for safe and reproducible evaluation of cortical functions, now used at several domestic and international sites, with commercialization progressing. Through these initiatives, we aim to build a safe, reliable, and fair ecosystem for consumer neurotechnology.

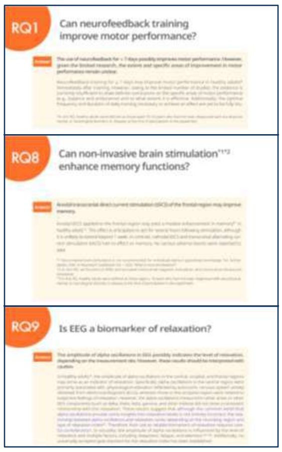
Development of Guidebooks for Consumers and Developers

We created a common language and practical guidance for Neurotechnology, covering both everyday use and pathways toward commercialization. Vol.1 organizes core concepts, major measurement and intervention methods, and key risks and precautions in a clear format, offering a shared foundation for consumers and developers to judge product value. Vol.2, designed as a handbook for responsible development, systematizes requirements related to regulation (advertising rules, medical-device boundaries, and protection of personal and neural data), safety, scientific validity, and consumer-facing information. Their content is aligned internationally through dialogue with multiple global organizations.



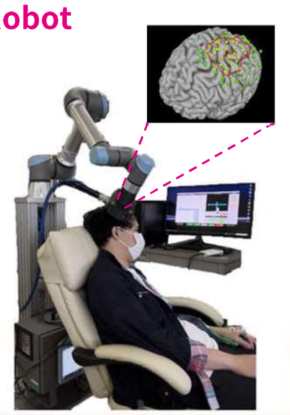
Evidence Consolidation of Non-Medical Neurotechnology

Consumer neurotechnology operates outside the strict regulatory framework used in medicine, which makes this area prone to misunderstanding and inflated expectations. To address this, our project focused on the non-medical domain and defined 12 key questions—for example, "Does neurofeedback enhance motor performance?", "Does non-invasive stimulation improve memory?", and "Is EEG a marker of relaxation?". We assessed the effectiveness, safety, and reliability of each topic through systematic reviews and published the results in the Evidence Book, which provides concise conclusions and the supporting evidence for each question. More than 40 researchers from six countries, from undergraduate students to professors, contributed to the reviews, bringing diverse perspectives. Several of the reviews are also published as preprints or peer-reviewed original papers.



Automation of Physiological Assessment: Development of a TMS Robot

Transcranial Magnetic Stimulation (TMS) non-invasively stimulates the brain with short magnetic pulses, allowing evaluation through responses such as hand muscle activity. We developed a TMS robot that performs this assessment safely and accurately in an automated manner. With this system, even non-experts can obtain high-quality measurements in a short time, improving reproducibility and throughput. This enables robust multi-site studies of neurophysiological effects. The TMS robot is now safely operated at multiple sites in Japan and abroad, and commercialization is in progress. Our next step is to integrate additional physiological signals—EEG, pupil diameter, ECG, EMG—to estimate brain states and autonomously optimize stimulation patterns. Although the current system focuses on motor-cortex function, multi-signal integration will allow extension to other functional domains and support autonomous exploration of new stimulation protocols.



Mitsuaki Takemi

Associate Professor, Graduate School of Advanced Science and Engineering, Hiroshima University

Graduated from the Faculty of Science and Technology, Keio Uni in 2011. Completed the Doctoral Program at the Graduate School of Science and Technology in 2015, earning a Doctor of Engineering degree. Subsequently worked as a postdoctoral researcher/tenure-track faculty member at the Danish Research Center for Magnetic Resonance (Denmark), the Graduate School of Education, The University of Tokyo, and the Graduate School of Science and Technology, Keio Uni. Assumed current position in 2025. Specializes in neurotechnology and motor control.

Future Prospects

In line with global trends in rule-making, the next five years will focus on implementation. First, together with domestic academic societies, we are developing educational materials—including lecture videos, experimental demonstrations, and Python exercises—and will publish them in Japanese and English. Our aim is to establish shared concepts and procedures and eventually to help align international discussions regarding Neurotechnology governance. In parallel, we will expand our international evidence-evaluation network so that results from different countries can be cross-referenced, accelerating building trust in neurotechnology. Finally, inspired by Japan's "Foods with Function Claims" framework, we will propose a two-tier scheme for "Devices with Function Claims" through peer-reviewed publications, with the goal of creating practical standards that are acceptable to developers, researchers, and users.

Ryoji Onagawa

Systematic Review Team Leader

JSPS Overseas Research Fellow / Postdoctoral Researcher, Queen's University

Published one peer-reviewed systematic review as a co-first author (Onagawa et al., 2023)

Ikko Kimura

Postdoc Researcher, Danish Research Centre for Magnetic Resonance

Published one peer-reviewed systematic review as a co-first author (Kimura et al., 2024)

Internet of Brains

国立研究開発法人 科学技術振興機構 ムーンショット型研究開発事業 ／ 株式会社国際電気通信基礎技術研究所
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Communication Infrastructure with Society

「Neu World」

Ryu Miyata, Science Communicator, Araya Inc.

IoB Fundamental Technologies

Moonshot Research and Development Program Goal 1 Kanai Project

Overview

"Neu World" is a science communication project for the "Internet of Brains (IoB)" Kanai Project, part of Moonshot Goal 1. While IoB advances cutting-edge research in neuroscience and AI to realize new ways of living, a communication gap exists between this research and daily life, which cannot be bridged by research presentations alone. We launched Neu World as a place for anyone who want to join. Employing Sci-Fi Prototyping methods, Neu World was born from the desire to co-create a new world together with creators (such as manga artists and novelists), researchers, and the public. We do this by producing original sci-fi works and enjoying diverse opinions, like "I want this kind of world," or "This future seems a bit off."

A New World Created Through Sci-Fi

Works Neu World Key Visual © Ququ

Based on the hypothesis of the applicability of Sci-Fi Prototyping to science communication, "Neu World" has established a science communication flow. This flow aims to foster dialogue and co-creation with the public about how to socially implement cybernetic avatar technologies, focusing on BMI, for the future. This is centered around the production and release of original sci-fi works.

STEP 1: Co-imagination: Creating Sci-Fi Works from Shared Imagination Focused on IoB research and development, citizens, creators, and researchers gather to communicate about diverse future possibilities. From this, original sci-fi works are produced. Examples: Interactive talk events, small-group workshops, dialogues between researchers and authors, etc.

STEP 2: Co-mmunication: Releasing, Disseminating, and Amplifying Sci-Fi Works The produced sci-fi works are released. Through collaborations with media and others, we aim to reach even those not usually interested in science. We aim to create a communication platform where diverse people can share their anxieties and hopes for the future through reactions to the works on social media and other channels.

STEP 3: Co-Creation: Promoting Co-Creative Activities Toward the Future We develop activities to evolve individual values, approaches to societal issues, and ideas through deeper dialogue. We aim to update the future visions sought by the Moonshot program and foster new co-creative activities with diverse stakeholders. Examples: Production and deployment of communication tools for use in schools and museums, analysis of collected opinions, release of results, and holding discussions, etc.

Future Outlook

What comes to mind when you hear the word "future"? Amidst daily advancing science and technology and an increasingly complex society, imagining the future has become progressively more difficult. The tools that help us imagine such a future without strain were in my favorite manga and novels. "Neu World" embodies the desire to create the next chapter of this world—this ultimate ensemble drama—together, based on the perspectives of researchers, creators, and all of you. Each and every one of you is the main character of this world. Let's advance our respective stories together.

Release of Sci-Fi Works Themed on Moonshot Goal 1 Research

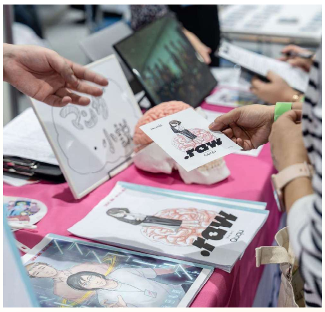
Neu World produces sci-fi works not as project visions or predictions, but as catalysts for dialogue to build the future together with society. As of September 2025, a total of five works (three manga, two novels) are available for free on the official Neu World website. We plan to release more new works sequentially.

©Ququ ©Author Ningen Rokudo/Illustration Keiko ©ReijiNagata ©KuuTanaka ©Author Katsuie Shibata / Illustration maniko

Toward Transnational Citizen Dialogue

To promote international communication and visualize bottom-up diversity of values, we are conducting a collaborative project with the Institute of Neuroethics (IoNx), a U.S.-based think tank specializing in neuroethics. In this project, we are creating survey tools for dialogue both domestically and internationally, and conducting communication activities abroad. In August 2025, we held a workshop in Osaka and Kobe themed "What if you could 'design' your memories freely?" and a panel discussion at the Osaka-Kansai Expo on the ethical, legal, and social implications (ELSI) of neurotechnology.

Creation of a Communication Infrastructure with Society



Centered on talk events and workshops, we conduct activities to raise awareness about IoB research and foster dialogue about the future. Each event generates communication from different perspectives due to the diversity of participants. We are developing content with consideration for DE&I (Diversity, Equity, and Inclusion), including developing initiatives through collaboration with educational institutions and stakeholders seeking science communication programs, providing Japanese translations and audiobooks of the works, offering sign language support at events, and holding events in regional areas.

Ryu Miyata

Science Communicator, Araya Inc.

Handles science communication related to IoB and Araya's research in the R&D Department at Araya Inc. Also active as an independent science communicator. Aiming to realize "a society free from stagnation," he engages in science communication activities through events and exhibitions that foster dialogue about the future of science, technology, and society. Member of the Science Fiction and Fantasy Writers of Japan (SFWJ).

Project Members

Hitomi Mottion / Yukie Sonoyama / Tomoyo Kobayashi / Sei Takeda / Yusuke Sugita / Kazuto Dobashi / Misaki Ozawa

※All members are Science Communicators

Internet of Brains

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