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)

IoB Middleware

Moonshot Research and Development Program Goal 1 Kanai Project

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**

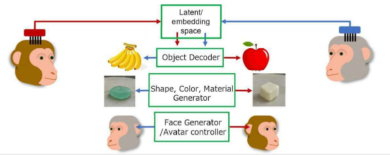


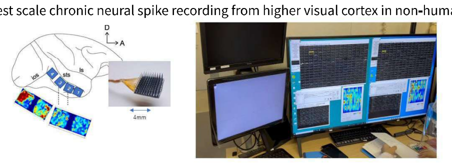
Image Reconstruction Technology Based on Neural Information from Higher-Order Visual Cortex

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.

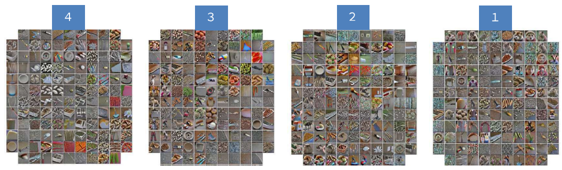
Leveraging the multimodal foundation model CLIP—which learns shared representations across images and language—we developed an information-processing architecture capable of bidirectional information transformation between brain activity and AI embeddings through supervised learning (learning with explicit 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)



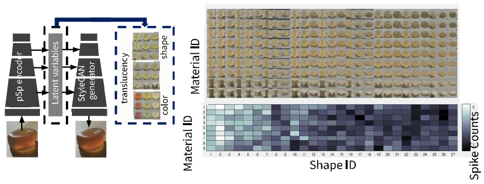
Odd-numbered segments: Viewed image →
Even-numbered segments: Reconstructed image →

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

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

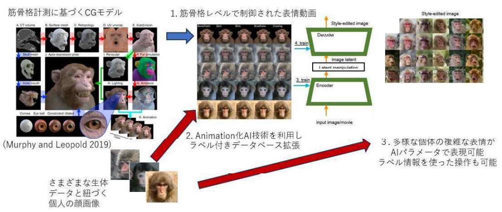
Decoding the Translucency of Objects Based on Neural Information

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).



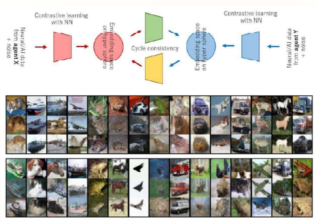
CA Development Using Generative AI

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).

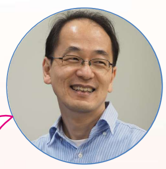


Top: Original image, Middle: Reconstructed image, Bottom: Reconstructed image after transfer

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

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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