A Framework for Understanding the Neural Underpinnings of Symbolic and Non-Symbolic Communication Based on Global Synchronization in Human Brain Activity

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Abstract

We propose a framework for understanding the neural underpinning of communication-based processes, using electroencephalogram (EEG) synchronization. The framework comprised four stages: (i) characterization of the target communication in a two-dimensional space defined by symbolic/embodied (non-symbolic) and voluntary/involuntary processes, (ii) a focus on the level of synchronization analysis on an ontological hierarchy, (iii) a construction of a neurocognitive model to explain neural mechanism, and (iv) empirical hypothesis testing of neural underpinning with model-based EEG connectivity neurofeedback processes. We claim that following the framework will advance our understanding of neural dynamics and mechanisms for communication. During this study, we analyzed two EEG experiments, while implementing two former stages: the formation of symbolic communication changing from voluntary to involuntary and embodied communication competing between voluntary and involuntary. Their outcome was a hypothesis that three brain regions were involved in interpreting symbols, motor intentions, and social coordination. Finally, we described the advantages and limitations of the proposed framework, following a discussion concerning its operational validation in the latter stage.

Keywords: Communication, Framework, Synchronization, Electroencephalogram, Neurocognitive modeling

1. Introduction

Human communication takes various modalities, such as using symbols (*symbolic communication*) and body movements (*embodied*, and often *non-symbolic, communication*), which enables communication with others. Therefore, the neural underpinning of symbolic and non-symbolic communication and its relationship to neural synchronization within and between the brains are currently being investigated. However, although such studies on the neural underpinning of these communication systems have been conducted independently between the symbolic and non-symbolic, differences and similarities between them are still not clearly understood. Thus, by devising a comprehensive framework for explaining these communication modalities, we can discuss a unified neural underpinning for them.

Hence, we propose a framework for understanding the neural underpinning of symbolic and non-symbolic communication systems from the viewpoint of synchronization. The framework comprised four stages:

(i) Characterization of the target communication in a space defined with two axes: symbolic/embodied (non-symbolic) and voluntary/involuntary,

(ii) A focus on the level of synchronization analysis on an ontological hierarchy of "micro-macro loop chains" from individual neural activities to social behavior, in which the upper level is organized from and constrains the lower level,

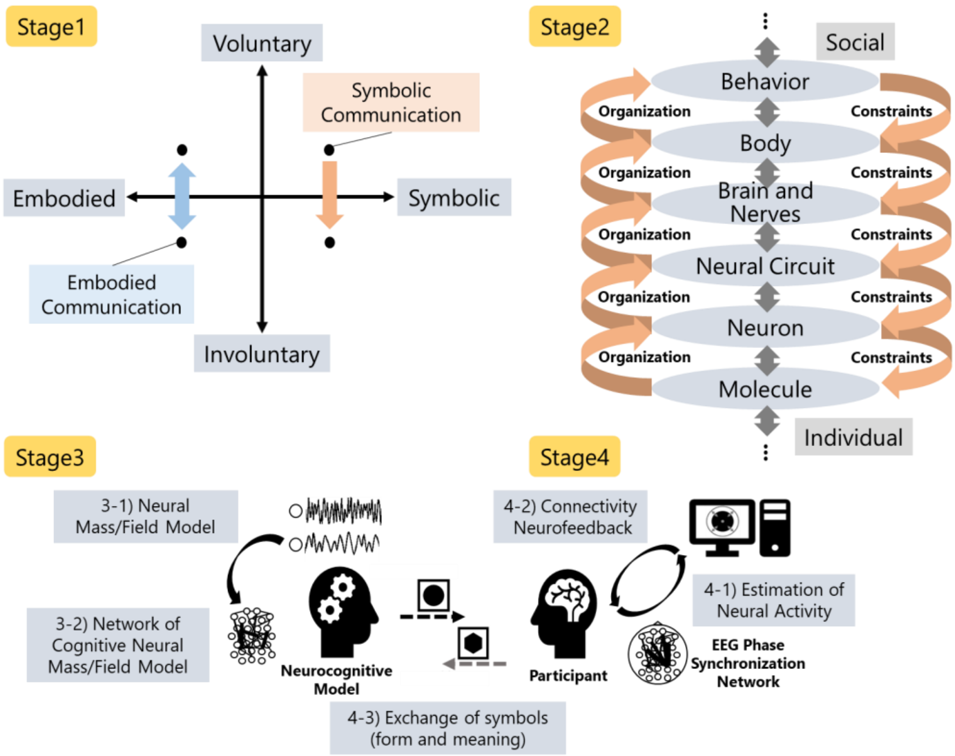

Fig. 1. A Framework for Understanding the Neural Underpinning of Symbolic and Non-Symbolic Communication. (Stage 1) A two-dimensional space to characterize communication modality. The horizontal and vertical axes were symbolic vs embodied and spontaneous vs involuntary, respectively. The two communication experiments summarized in this paper are illustrated with red and blue arrows. (Stage 2) A conceptual diagram showing a micro-macro loop chain with organizations and constraints. Upper levels focused on the social phenomena, whereas the lower focused on the individual phenomena in this ontological hierarchy. (Stage 3) Steps to construct a neurocognitive model, using the neural mass/field model and (Stage 4) to empirically validate the neural underpinning, using an EEG connectivity neurofeedback, during communication with a virtual partner based on the neurocognitive model.

to conduct empirical measurements during communication,

(iii) The construction of a neurocognitive model to explain neural mechanisms, and

(iv) Empirical hypothesis testing, with EEG connectivity neurofeedback methods, based on the model.

By going through these four stages, we expect to understand neural dynamics and communication mechanisms of communication deeply.

This paper also provides an overview of the findings from two EEG experiments on symbolic and non-symbolic communication, following this framework, and presents a working hypothesis of the neural underpinning of a communication system. Finally, we summarize the proposed comprehensive framework, describe its advantages and limitations, and discuss further operational validation methods of the neural underpinning hypothesis in the brain.

2. A Framework for the Neurological Understanding of Communication

2.1. *A two-dimensional space to characterize human communication*

At first, we positioned the target communication as a research subject in a two-dimensional space according to the target's communication modality. The space comprised two axes: the symbolic/physical (non-symbolic) axis and the voluntary/involuntary axis. In Fig. 1 (Stage 1), our two EEG experiments that show communication were placed on the space.

Note that the positioning is either a point or a changing path in the space. Targets in this paper were represented as paths having directionalities since we were interested in dynamic phenomena, such as the formation of communication systems and intentional switching during communication processes. This stage makes it possible to characterize the target communication clearly.

2.2. *The micro-macro loop chain on cognitive neuroscience*

In the second stage, we examined which ontological level should be focused on to empirically investigate the targeted communication in the first stage. Therefore, we proposed a “micro-macro loop chain” with emergent and constrained feedback loops among ontological levels (Fig. 1, Stage 2). This concept is inspired by the micro-macro loop in social science (organization theory[1] and economics[2]), in which micro information is connected to macro information which is then fed back to the micro-level.

The critical issue is the level of focus. Once the target level is determined, upper and lower levels become apparent. Then, we conducted empirical measurements and analyses to clarify the self-organization and constraints between the target level and the upper/lower levels.

2.3. *Computational modeling using a neural mass/field model*

In the third stage, we construct a computational model of phenomena at the target level (Fig. 1, Stage 3) through two steps: 3-1) building a model for the lower level and 3-2) making a network of the lower level models. This model construction approach is a sort of constructive approach[3], which is complementary to predictions and inferences from laboratory experiments and is effective to understanding complex phenomena and mechanisms. Following this approach, we construct a model or system that is based on a specific prediction or inference. Although the model is difficult to validate in actual situations, we run the model on a computer to verify it by comparing the computation results with real-world phenomena. The constructive approach is especially beneficial for neuroscientific studies of communication, focusing on the human brain.

Various models have been explored in computational neuroscience, starting with neuron models, neural mass models, such as the Wilson-Cowan model[4], next-generation neural field models[5], and neurocognitive models. By exploring what conditions are necessary for neural networks and the neural underpinning of human communication with a constructive approach, using these models, an understanding on the self-organization and constraints in the micro-macro loop chain will be achieved. While it is necessary to validate the constructed neurocognitive model by corresponding with actual phenomena, it is also possible to investigate more comprehensive models based on specific phenomena.

2.4. *A model-based EEG connectivity neurofeedback*

In the fourth stage, we 4-1) estimate neural activities during communication with a virtual partner[6,7], using a computational model constructed in the third stage, 4-2) conduct an EEG connectivity neurofeedback[8,9], and 4-3) perform an operational validation of neural mechanism of human communication. Specifically, the functional connectivity in the human brain is estimated through quantification of neural synchronization processes, following feeding to a computational model to reflect this quantification in the model’s communicative behavior (e.g., decision making). Manipulating the model also allowed us to approach the empirical validation from the angle of indirect neural causalities.

3. EEG Recording Experiments

This section presents an overview of our two communication experiments, working on the proposed framework. For details on experiments and results, please refer to [10,11] for the former, and [12] for the latter.

3.1. *Symbolic communication tasks*

The symbolic communication task (red arrows in Fig. 1, Stage 1) is a coordination game[13,14], in which two participants performed a task through an exchange of symbols only. The game comprised a laboratory experiment, based on experimental semiotics[15,16], which allowed us to observe the emergence of artificial language by deliberately restricting the means of communication.

This task was designed to observe the emergent process of symbolic communication. Specifically, participants were required to move their avatars, placed in one of the four rooms, to the same room as their partner, only by exchanging predetermined and meaningless figures (Fig. 2). The task was designed such that it was impossible to successfully achieve the task without inferring implicit intentions as well as the correspondence between figures and rooms.

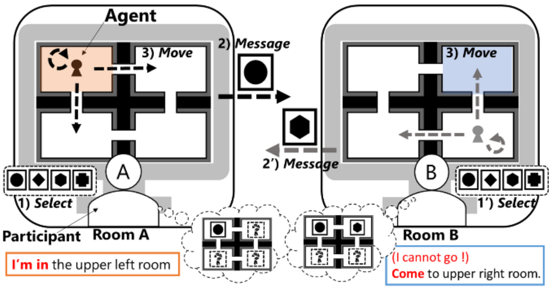

Fig. 2 An overview of the symbolic communication task.

3.2. *The Look This Way! task*

Regarding embodied non-symbolic communication, we proposed a new experimental paradigm called the "Look This Way!" task. In this task, pairs of participants played "janken" (rock-paper-scissors), followed by a finger-wagging task that was a modified version of a traditional Japanese game "Acchi-Muite-Hoi."

This task was designed to observe the representation and understanding of dynamic motor intentions when two participants switched cooperation and competition with each other (blue arrows in Fig. 1, Stage 1; Fig. 3). Specifically, during the "rock-paper-scissors," the two participants involuntary synchronized their rhythms when they shook their arms. In contrast, the subsequent "Look This Way!" task required voluntary *competitive* motions, particularly pointing the finger in a different direction from the partner. By comparing neural and physical activities with that of cooperative and scramble finger-pointing conditions, this experimental design allowed us to observe understanding and switching

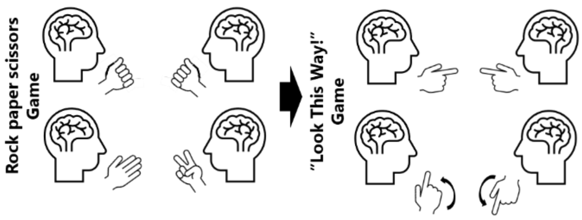

Fig. 3. An overview of the look this way! task.

dynamic motor intentions that were involved in embodied communication.

3.3. *A working hypothesis of the neural underpinning of symbolic and non-symbolic communication systems*

The target level of the hierarchy in the experiments described in this paper is the neural activity during EEG recordings, with the upper level being the whole brain as functional connectivity between brain regions, and the lower level being the hierarchy at the neuronal level. The EEG recordings reflect a neural oscillation by electrical activities, in which the sum of the action and synaptic potentials of neurons appears with a certain rhythm. Neural oscillation is used to observe self-organization at the level of the functional network in the brain. On the contrary, neural oscillation is also maintained in a certain state due to the constraints of the brain network and is the constraint on neuronal activities. Epilepsy, for example, can be regarded as a condition, in which for some reasons, constraints of the brain network (or neural oscillation) are broken, and neurons become spontaneously and continuously active and synchronized.

Actually, we observed the neural activations and synchronization between the frontal and right centro-parietal regions from the former EEG experiment, and activations of the left fronto-central and right centro-parietal regions from the latter. The results suggested that three brain regions were involved in interpretating symbols, motor intentions, and social coordination processes. Therefore, we proposed a working hypothesis on the neural underpinning of symbolic and non-

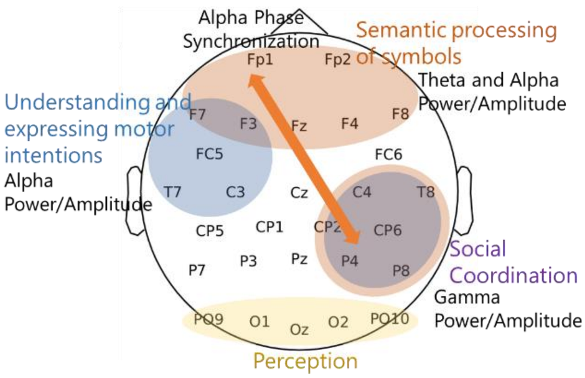

Fig. 4. A neural underpinning hypothesis for symbolic and non-symbolic communication processes

symbolic communication processes, as described in Fig. 4. We will also perform stages 3 and 4 in the proposed framework to validate this working hypothesis.

4. Discussions and Conclusion

We propose a framework, comprising four stages, to understand the neural underpinning of symbolic and non-symbolic communication. One advantage of the framework is the unified handling of symbolic/non-symbolic communication processes. Actually, we performed symbolic and non-symbolic communication experiments according to the framework. As a result, we proposed a new working hypothesis on neural underpinnings of symbolic and non-symbolic communication processes.

Meanwhile, although the validity of the framework has not been demonstrated yet, it is necessary to achieve this validation by confirming the working hypothesis based on the latter two stages of computational modeling, and the operational experiment, using a model-based EEG connectivity neurofeedback of human communication processes. While we focused on human communication processes so far, to consider the mechanisms of communicating with animals and machines, we need to also specify important factors to distinguish among humans, animals, and machines. It is therefore expected that the proposed framework will be helpful for such universal communication processes, including its understanding.

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References

1 K. Imai and I. Kaneko, Network Organization Theory. Iwanami Shoten, 1988 (in Japanese).

2 Y. Shiozawa, Introduction to Complex Systems Economics. Chikuma Shobo, 2020. (in Japanese)

3 T. Hashimoto, "The Emergent Constructive Approach to Evolinguistics: Considering Hierarchy and Intention Sharing in Linguistic Communication," *J. Syst. Sci. Syst. Eng.*, Vol. 29, pp. 675–696, October. 2020.

4 H. R. Wilson and J. D. Cowan, "Excitatory and Inhibitory Interactions in Localized Populations of Model Neurons," *Biophys. J.*, Vol. 12, No. 1, pp. 1–24, 1972.

5 Á. Byrne, D. Avitabile, and S. Coombes, "Next-generation neural field model: The evolution of synchrony within patterns and waves," *Phys. Rev. E*, Vol. 99, No. 1, January. 2019.

6 G. Dumas, G. C. de Guzman, E. Tognoli, and J. A. S. Kelso, "The human dynamic clamp as a paradigm for social interaction," *Proc. Natl. Acad. Sci.*, Vol. 111, No. 35, pp. E3726–E3734.

7 V. Kostrubiec, G. Dumas, P. G. Zanone, and J. A. Scott Kelso, "The virtual teacher (VT) paradigm: Learning new patterns of interpersonal coordination using the human dynamic clamp," *PLoS One*, Vol. 10, No. 11, p. e0142029, 2015.

8 A. Mottaz, M. Solcà, C. Magnin, T. Corbet, A. Schnider, and A. G. Guggisberg, "Neurofeedback training of alpha-band coherence enhances motor performance," *Clin. Neurophysiol.*, Vol. 126, No. 9, pp. 1754–1760, September. 2015.

9 A. Yamashita, S. Hayasaka, M. Kawato, and H. Imamizu, "Connectivity Neurofeedback Training Can Differentially Change Functional Connectivity and Cognitive Performance," *Cereb. Cortex*, Vol. 27, No. 10, pp. 4960–4970, October. 2017.

10 F. Masayuki *et al.*, "Characteristics and connectivity of phase synchrony between success and failure group during symbolic communication task," *Proc. 27th Annu. Conf. Japanese Neural Netw. Soc.*, pp. 53–54, 2017.

11 M. Fujiwara *et al.*, "Changes in Phase Synchronization of EEG during Development of Symbolic Communication Systems," *Adv. Cogn. Neurodynamics (VI)*, pp. 327–333, 2018.

12 M. Fujiwara, M. R. V. Sanchez, S. Mishima, T. Hashimoto, and H. Wagatsuma, "An EEG Power Analysis with Hyperscanning EEG-Motion-Gaze data in the "Look This Way!" Game: A Pilot Study." (in preparation)

13 T. Konno, J. Morita, and T. Hashimoto, "Symbol communication systems integrate implicit information in coordination tasks," *Adv. Cogn. Neurodynamics (III)*, pp. 453–459, 2013.

14 G. Li, T. Konno, J. Okuda, and T. Hashimoto, "An EEG Study of Human Mirror Neuron System Activities During Abstract Symbolic Communication,"*Cogn. Neurodynamics (V)*, pp. 1–6, 2015.

15 B. Galantucci and S. Garrod, "Experimental Semiotics: A Review," *Front. Hum. Neurosci.*, Vol. 5, February, pp. 1–15, 2011.

16 B. Galantucci, "Experimental Semiotics: A New Approach for Studying Communication as a Form of Joint Action," *Top. Cogn. Sci.*, Vol. 1, No. 2, pp. 393–410, April. 2009.

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