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Research Article

Proposing Discussion Framework and Hypothesis for Neural Underpinnings of Human Symbolic and Embodied Communication from Synchronization Viewpoint

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ABSTRACT

A framework for discussing the neural underpinning of communication processes is proposed from the perspective of synchronization. This framework comprises four stages: (i) characterizing the target communication in a two-dimensional space defined by symbolic/embodied (non-symbolic) and voluntary/involuntary processes, (ii) focusing on the level of analysis of synchrony on an ontological hierarchy, (iii) constructing a neurocognitive model to simulate neural dynamics, and (iv) testing an empirical hypothesis on the neural underpinning of communication through model-based electroencephalography (EEG) connectivity neurofeedback in communication experiments with the cognitive neural mass/field model. We performed two EEG experiments, implementing the former two stages: the formation of symbolic communication, in which communication changed from voluntary to involuntary, and intentional switching in embodied communication, which involves switching between voluntary and involuntary behavior. The findings on communicative brain activities from these experiments culminated in the hypothesis that three brain regions are involved in interpreting symbols and motor intentions as well as in social coordination, in which one region might be shared by two modalities and the other two are specific to each modality. As we could perform the experiments and their analyses and derive a working hypothesis based on the framework, we claim that the proposed framework may be vital for investigating the neural underpinnings of communication in two different modalities in a unified manner.

1. Introduction

Human communication involves various modalities, using symbols such as letters and icons (*symbolic communication*) and body movements such as facial expressions and gestures (*embodied*, and often, but not limited to, *non-symbolic communication*). Although the neural underpinning of both symbolic and embodied communication has been studied, mostly independently between the symbolic and embodied modalities, differences and similarities between these two modalities remain unclear. With a comprehensive framework for discussing the relationships among communication modalities, we may be able to understand their unified neural underpinnings.

This study proposes a framework for discussing the neural underpinnings of symbolic and embodied communication systems from the viewpoint of

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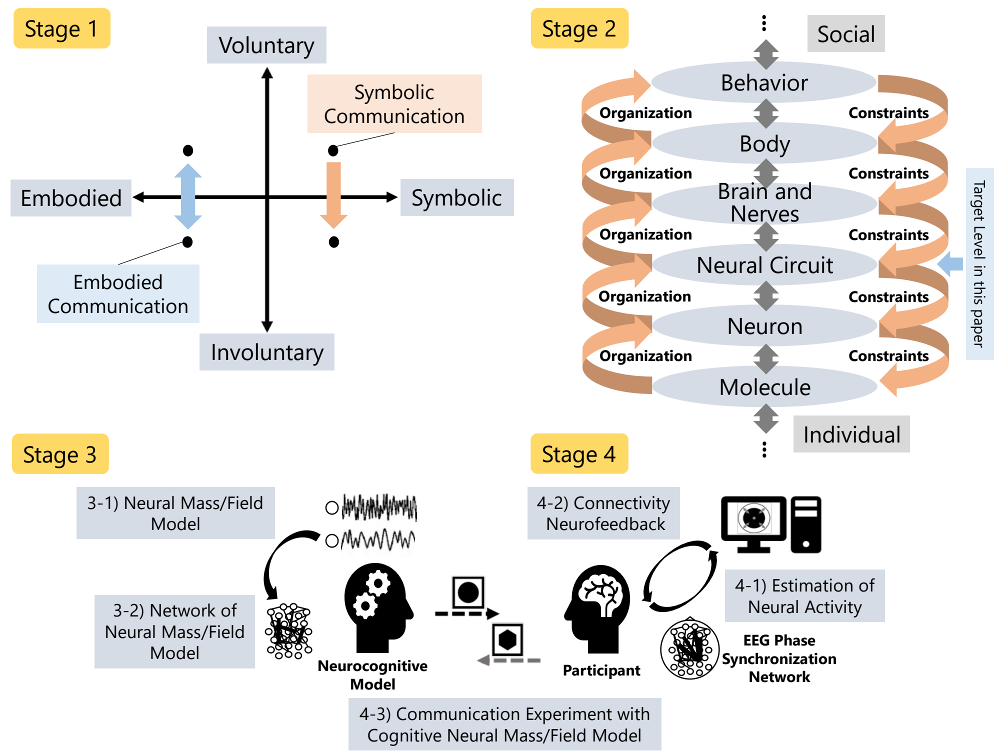

Fig. 1. A framework for discussing the neural underpinning of symbolic and embodied communication. (Stage 1) A two-dimensional space to characterize communication modality. The horizontal and vertical axes were symbolic-embodied and voluntary–involuntary, respectively. The two communication experiments summarized in this paper are illustrated with red and blue arrows, respectively. (Stage 2) A conceptual diagram depicting a micro–macro loop chain with organizations and constraints. The upper levels focused on the social phenomena, whereas the lower levels focused on the individual phenomena in this ontological hierarchy. The target in this paper is the level of neural circuit. (Stage 3) Steps to construct a neuro-dynamics model, using the neural mass/field model for the target level in this paper, and (Stage 4) to empirically validate the neural underpinning and its causal mechanism for cognitive function, using an electroencephalography connectivity neurofeedback, during communication with a cognitive neural mass/field model.

synchronization. Our framework aims to treat different communication modalities in a unified manner. Synchronization phenomena are universally observed at different scales and levels of hierarchy, such as intercellular [1], intracerebral [2], interbrain [3], and collective and social behaviors [4]. In particular, neural synchronizations within and between the brain in symbolic [5] and embodied communication [6] have been investigated. Therefore, by focusing on such synchronization phenomena, human and non-human communication can be treated in a unified manner.

The framework comprises the following four stages:

(i) Characterizing the target communication in a space defined with two axes: symbolic/embodied (non-symbolic) and voluntary/involuntary,
(ii) Focusing 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 and constrains the lower level in order to conduct empirical measurements during communication,
(iii) Constructing a neuro-dynamics model to explain neural mechanisms, and
(iv) Testing an empirical hypothesis using the electroencephalography (EEG) connectivity neurofeedback method based on the cognitive neural mass/field model.

Investigating these four stages, we expect to deeply understand the neural dynamics and mechanisms of communication.

The remainder of this paper is organized as follows. In Section 2, each stage of the proposed framework is explained in each subsection. We provide an overview of the findings from two EEG experiments on symbolic and embodied communication, performed according to our framework, in Sections 3.1 and 3.2, respectively. A working hypothesis for the neural underpinning of communication systems is proposed in Section 4. Finally, in Section 5, we summarize the proposed comprehensive framework, describe its advantages and limitations, and discuss further operational validation methods for the neural underpinning hypothesis in the brain.

2. Framework for the neurological discussion of communication

2.1. *Two-dimensional space to characterize human communication*

First, we positioned the target communication as a research subject in a two-dimensional space, according to the target's communication modality. The space comprises two axes: symbolic/embodied (non-symbolic) and voluntary/involuntary. The former axis represents a difference in communication modality, whereas the latter represents whether the behavior is intentional. In Fig. 1 (Stage 1), the two EEG experiments that demonstrate communication were placed in the space.

Positioning is either a point for a fixed communicative phenomenon or a path for a developmental/changing process in space. The targets in this paper are represented as paths with directionalities because we are interested in dynamic phenomena, such as the formation of communication systems (Section 3.1) and intentional switching during communication processes (Section 3.2). This stage makes it possible to characterize the target communication clearly.

2.2. *Micro–macro loop chain in 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. Hence, we propose a "micro–macro loop chain" [7] with feedback loops of emergence and constraints among ontological levels of communication phenomena (Fig. 1, Stage 2). An emergence ((self-)organization), where the hierarchy of levels in natural systems is assumed, should appear as a property at the upper level as a whole, and not merely as the sum of the properties of its parts due to the interaction among parts at the lower level; constraints indicate that the property at the upper level governs the parts at the lower level [8]. For example, although neurons as a physical entity can take numerous states, they must be organized into a specific neuronal population or neural circuit in order to perform a certain function. By contrast, the neural activity of neurons is constrained by population and circuit. Furthermore, the organization of the intracerebral and the whole brain by coordination within the neural circuits and brain regions achieves higher-order cognitive functions. Simultaneously, coordination within neural circuits and brain regions is constrained in achieving and maintaining cognitive function. Epileptic seizures can be interpreted as symptoms in which the constraint is defeated, and the entire cerebral nervous system is synchronized. We assumed that organizations and constraints exist at each level in the brain, and they work to realize various cognitive functions.

The concept of a "micro–macro loop chain" is inspired by two related concepts. One is the hierarchy of emergence in tacit knowing [8], in which elements form the comprehensive whole as an emergence, which is tacit knowing epistemologically and emergence ontologically, and the whole becomes an element at the consecutive emergence, which constitutes a hierarchical structure. The other is the micro–macro loop in social science (organization theory [9] and economics [10]), in which micro information is connected to macro information, which is then fed back to the micro level.

A critical issue in empirical research is the level of focus. Once the target level was determined, the upper and lower levels became apparent. Hence, empirical measurements and analyses were performed to clarify the self-organization and constraints between the target and 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) in two steps:3-1) building a model for the lower level and 3-2) thereby creating a network of the lower-level models. This model construction is a sort of constructive approach [11,12,13] that is complementary to predictions and inferences from laboratory experiments and is effective in understanding complex phenomena and their mechanisms. Following this approach, we construct a model or system based on a specific prediction or inference of the targeted phenomena. Although validating the model in actual situations can be difficult, we run the model on a computer for verification by comparing the computation results with real-world phenomena. This constructive approach is beneficial for neuroscientific studies of communication, especially when focusing on the human brain, where the problem of invasiveness arises.

Various types of neurodynamic models [14,15] have been explored in computational neuroscience, starting with neuron models, neural mass models, such as the Wilson–Cowan model [16], next-generation neural field models [17], and neurocognitive models. By exploring the conditions necessary for neural networks and neural underpinning of human communication with a constructive approach using these models, an understanding of the (self-)organization and constraints in the micro–macro loop chain will be achieved. While validating the constructed neurodynamic model by corresponding it with actual phenomena is necessary, more comprehensive models can also be investigated based on specific phenomena.

We mainly focused on a neural mass/field model because the target level was set at the “neural circuit” in this paper. However, for discussing and understanding neural underpinnings, neural models that estimate the organization and constraints in the phenomena at higher and lower levels, respectively, need to be considered rather than a neural mass/field model.

2.4. *Model-based EEG connectivity neurofeedback*

The fourth stage, comprising three steps, involves the operational validation of the neural mechanism of human communication. Neural activity during communication should be estimated (4-1). This can be achieved by conducting a communication experiment with a virtual partner [18,19] using the computational model constructed in the third stage. In this experiment, the computational model plays the role of the communication partner; therefore, communication can be controlled in the experiment. This experiment is not only a measurement, but also includes EEG connectivity neurofeedback (4-2). A coupled neurofeedback method [20,21] was devised to train experimental participants to manipulate global neural activity as a technique to improve cognitive performance. The neural activity of participants can be targeted (controlled to some extent) using this technique, which allows us performing operational validation of the neural mechanism of human communication (4-3).

Specifically, for discussing the neural underpinning of communication from the viewpoint of neural synchronization, functional connectivity in the human brain is estimated through quantifying neural synchronization processes. This quantification is fed to a computational model to reflect the effect of functional connectivity on the communicative behavior (e.g., decision making) of the virtual partner. Manipulating the computational model and neural activities in the participants’ brain through connectivity neurofeedback allows us to approach the empirical validation from the perspective of indirect neural causalities.

3. EEG recording experiments

This section presents an overview of our two communication experiments with EEG recordings using the proposed framework. For details on the experiments

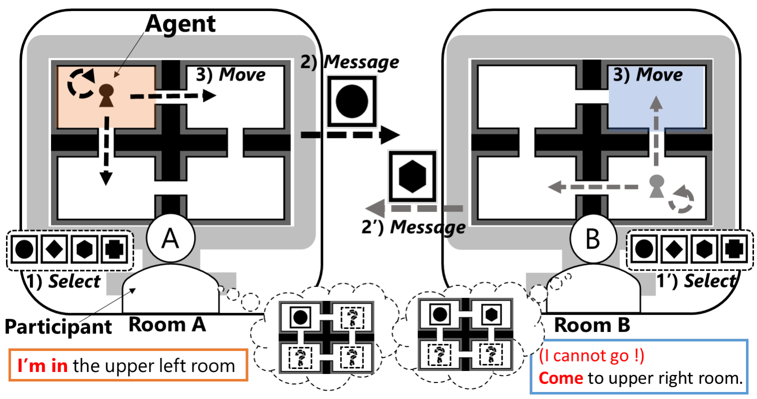

Fig. 2. An overview of the symbolic communication task.

and results, please refer to [22,23] for the former and [24] for the latter.

3.1. *Formation of symbolic communication*

We investigated the formation of symbolic communication using symbolic communication task (red arrow in Fig. 1, Stage 1). The task was a coordination game [25,26], in which two participants coordinated their behavior through exchanges of symbols only. The repetition of the task allowed us to observe the emergence of artificial language and communication systems by deliberately restricting the means of communication based on experimental semiotics [27,28].

This task was designed to observe the emergent process of symbolic communication. Specifically, the participants were required to move their avatars, placed in one of the four rooms, to the same room as their partners, only by exchanging predetermined and meaningless figures (Fig. 2). At the beginning of the task repetition, the participants interpreted the figures intentionally. They agreed on the meaning of the symbols as a code of figures and their meanings, and finally, the symbols could be used without intentional interpretation. The task was designed such that it was impossible to completely achieve the task without inferring implicit intentions as well as the correspondence between figures and rooms.

The EEG analysis revealed significant increases in the amplitude and phase synchronization in the low-(theta/alpha) and high-frequency (gamma) bands in the success group, but not in the failure group, when interpreting the meaning of the symbols as the partner's message in this task. These differences were observed in the frontal and right centro-parietal regions. These differences may reflect the organization's ability to achieve a higher cognitive function of communicative understanding of symbol meaning.

3.2. *Intentional switching in embodied communication*

Regarding embodied non-symbolic communication, we proposed a new experimental paradigm called "Look This Way!" game [24]. In this game, pairs of participants played "janken" (rock–paper–scissors phase), followed by a finger-wagging task (look this way phase) that was a modified version of a traditional Japanese game "Acchi-Muite-Hoi" (Fig. 3).

This task was designed to observe the representation and understanding of dynamic motor intentions when the two participants switched between cooperation and competition (blue arrow in Fig. 1, Stage 1). Specifically, during the rock–paper–scissors phase, the two participants involuntarily synchronized their rhythms as social coordination while shaking their arms. By contrast, the subsequent look this way phase required voluntary *competitive* motions, particularly pointing the finger in a different direction from that of the partner. By comparing neural and physical activities in cooperative and competitive finger-pointing conditions, this experimental design allowed us to observe intentional switching involved in embodied communication.

As a result, the power of the alpha and gamma bands significantly increased during cooperation compared with that during competition. This difference was observed in the left fronto-central and right centro-parietal regions. Differences in neural activity may

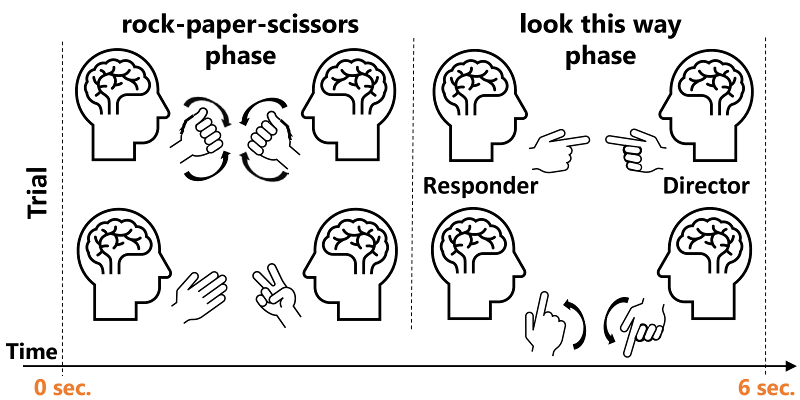

Fig. 3. An overview of the Look This Way! game.

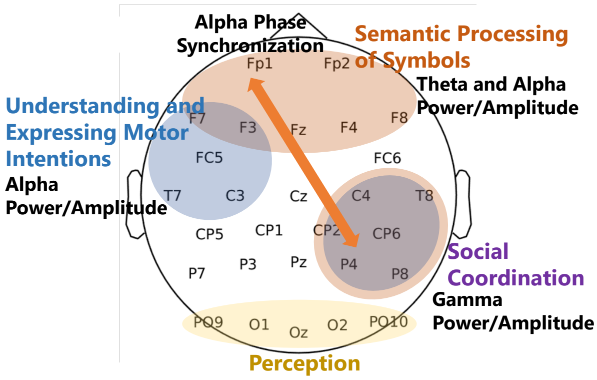

Fig. 4. A hypothesis of neural underpinning for symbolic and embodied (non-symbolic) communication processes. The channel location, represented by letters such as "Fp1," was based on the International 10–20 system.

reflect the organization of embodied communication which requires intentional switching.

4. Working hypothesis of the neural underpinning of symbolic and embodied communication systems

The target level of the hierarchy in the experiments described in this paper is the neural activity during EEG recordings, where the upper level is the whole brain as functional connectivity between brain regions and the lower level is the hierarchy at the neuronal level. The EEG recordings reflect a neural oscillation by electrical activity, in which the sum of the action and synaptic potentials of neurons appears with a certain rhythm. Neural oscillations are used to observe self-organization at the level of the functional network in the brain [29,30]. By contrast, neural oscillation is also maintained in a certain state owing to the constraints of the brain network, thus being considered a constraint on neuronal activity. For example, epilepsy can be considered a state in which the constraints of the brain network (or neural oscillation) are inadvertently broken, and neurons become spontaneously and continuously active and synchronized.

We observed neural activation and synchronization between the frontal and right centro-parietal regions from the former EEG experiment (Section 3.1) and activation of the left fronto-central and right centro-parietal regions from the latter (Section 3.2). The results suggest that the three brain regions were involved in interpreting symbols, motor intentions, and social coordination processes. Based on these findings on neural activity, we proposed a working hypothesis on the neural underpinnings of symbolic and embodied communication processes, as described in Fig. 4. As presented in the figure, the similarity of the neural underpinnings of the two modalities of communication is the activity of the gamma band in the right centro-parietal region, and the difference is the neural activity of the low-frequency (theta/alpha) band in the frontal and left fronto-central regions, which may reflect the difference between the two modalities. The long-range alpha band phase locking in the anterior–posterior direction may represent the possibility of coordination in the brain. Thus, these similarities and differences between the two modalities may be candidates for organizing and constraining the neural underpinnings of symbolic and embodied human communication. We will also perform stages 3 and 4 in the proposed framework to validate this working hypothesis.

5. Conclusion

We propose a framework comprising four stages to discuss the neural underpinning of symbolic and embodied (non-symbolic) communication. One advantage of this framework is the unified handling of two different modalities of communication processes: symbolic/embodied (non-symbolic). We performed and analyzed symbolic and embodied (non-symbolic) communication experiments according to the framework. We propose a new working hypothesis on the neural underpinnings of symbolic and non-symbolic communication based on the observed neural activities in communication processes. As we could perform the experiments and their analyses and could derive a working hypothesis based on the framework, the proposed framework may be vital for investigating the neural underpinnings of communication in two different modalities in a unified manner.

This framework aimed to understand the causal mechanism of communication by proceeding to stages 3 and 4. Namely, we attempt to validate that the hypothetical neural underpinning causally realizes the cognitive function of communication. In order to achieve this, the neural activity of the communication participants should be manipulated. This manipulation is possible using model-based connectivity neurofeedback. More specifically, in the case of symbolic communication, long-range alpha band synchronization in the anterior–posterior direction is trained using EEG connectivity neurofeedback [20,21] during a communication experiment between participants and the cognitive neural mass/field model. Furthermore, the cognitive neural mass/field model is analyzed theoretically and computationally to determine how neural connectivity modulates the cognitive function of communication for a mechanistic understanding of causality.

To date, we have focused on human communication processes to analyze the mechanisms of communication with animals and machines and to understand the evolution of communication. However, the important factors to distinguish among humans, animals, and machines need to be specified. Therefore, the proposed framework will be helpful in comprehending such universal communication processes.

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