

ミラーニューロンシステムの活動と記号コミュニケーションシステムの形成との関係についての脳波研究

The relationship between the mirror neuron system activity and the formation of symbolic communication systems found in an EEG study

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Abstract

To communicate with each other, we can use symbols to convey meaning. As human being, we can develop symbolic communication systems through repetitive interaction. What is the neural mechanism underlying this process? A prospective candidate is the mirror neuron system. Since its discovery, the mirror neuron system has been related to action understanding and gestural communication, whereas its involvement in the formation of symbolic communication systems is unclear. In the present study, we conducted a coordination game experiment by taking the experimental semiotics approach, in which the formation process of symbolic communication system was investigable. We employed electroencephalography to measure the mu band power suppression over the left sensorimotor cortex when the participants received messages from their partner, and use that as the index of the mirror neuron system activity for interpreting symbols. For those who performed well in the game, a significantly stronger mu suppression was found in the first half of the game than in the second half. As the communication systems should be formed in the first half of the game, the results of this study suggest that the mirror neuron system may be involved in the formation of symbolic communication systems in terms of simulation, i.e., interpreting other's message by simulating how the observer would mean when sending the same message. This simulation mechanism may benefit the symbolic communication at the forming stage.

Keywords — experimental semiotics, mirror neuron system, EEG, symbolic communica-

tion, mu suppression

1. Introduction

In daily life, we use language for communication with each other. But what if we do not have a shared language in advance? In fact, we can still understand each other through repetitive interaction. In such a process, new communicative protocols, i.e., communication systems were formed. What is the neural mechanism underlying this ability?

A number of physiological studies suggest that the answer to this question may lie within the mirror neuron system (MNS), which is a brain system that exhibits congruent neural activity between performing own actions and observing others' actions [21]. Many researchers consider it as the neural basis of a mechanism linking the performer of an action and its observer, in which sense the "action" becomes a "message" carrying "meaning" [20]. Accordingly, the MNS may actually provide a natural platform enabling gestural communication, from which language evolved [1, 4].

On the other hand, although the MNS may be involved in the understanding of gestures, what about the case of symbols, i.e., when the form-meaning mappings are arbitrary? Indeed, most words in human language are symbolic. Is the MNS also involved in symbolic communication?

In fact, it has long been suspected that symbols must be "grounded" or "embodied" in order to convey meanings. In other words, the meaning of words should be considered as deriving from experiences based on the bio-mechanical nature of bodies and per-

ceptual systems, and hence understanding of others' words in communication may require one to "simulate" the corresponding sensorimotor experiences of others in one's own mind [9, 4]. In particular, the discovery of the MNS provided strong support for this theory, and the MNS had been considered as an ideal candidate for the shared neural mechanism underlying both gestural communication and symbolic communication.

Nevertheless, the evidence for the involvement of the MNS in symbolic communication is very limited. There is evidence from functional magnetic resonance imaging (fMRI) studies found congruence between the neural representations of visually presented actions and corresponding linguistic phrases in Brodmann area (BA) 44 and the premotor areas of the brain [3, 2]. This finding suggested the possible existence of the MNS related to the understanding of symbols.

However, there were several critical issues to be clarified regarding the relationship between the MNS and the formation of symbolic communication systems. Firstly, the MNS activity was only examined in a passive situation where only the understanding process was involved, whereas the producing-understanding association is crucial in communication. Secondly, only preexisting language had been examined. As the form-meaning mappings are dynamic in symbolic communication, it is important to examine the MNS activity in the formation process of symbols. Thirdly, only somatotopic words, i.e., the words directly related to bodies and actions, were examined in previous experiments. Thus, the results need to be validated for non-somatotopic symbols. In sum, we need to examine the MNS activity in the formation process of symbols in a communication context, where the symbols are not directly related to bodies or actions.

We adopted the *experimental semiotics* approach to design our experiment. This approach especially concerns the process of the emergence of new symbolic communication systems in the laboratory [7]. For example, in a previous study [6], pairs of participants were invited to play a coordination game, in which they moved their agents in a grid of several rooms, aiming to meet each other in the same room. They

could communicate with each other by drawing on a special device, which worked in a way that made the use of standard graphic forms practically impossible, and hence drastically reduced the possibility of using preexisting communicative conventions [7]. Although the task was quite challenging at first, the players could succeed in it by developing communication systems through a number of rounds of repetitive interaction. In this way, the complete history of the development of new communicative conventions become investigable. Further, a simplified version of this game had been developed, enabling rapid emergence of communication systems and easier quantitative analysis of resultant protocols [12]. This experiment paradigm provides a practical way to investigate the formation process of symbolic communication systems.

To examine the MNS activity in the experiment, we recorded the electrical brain signals of the participants by electroencephalography (EEG) recordings when they interpreting messages, which were sent by their partners in the game. Previously, mu band power suppression over the sensorimotor cortex had been used as an index of the MNS activity in a number of studies [13, 14, 22, 16, 5]. The link between mu suppression and the MNS activity had been supported by fMRI [15] and repetitive trans-cranial magnetic stimulation (rTMS) [10] studies. Accordingly, aiming to clarify the involvement of the MNS in the formation process of symbolic communication systems, we measured the mu suppression over the sensorimotor brain areas in the EEG data collected in a coordination game experiment. In this paper, the details and the results of the experiment are demonstrated in the next sections. Based on the results, the relationship between the MNS activity and the formation of symbolic communication systems is discussed.

2. Methods

2.1 Task

In our experiment, pairs of participants were instructed to play a coordination game. The players sat in separate rooms, and needed to control their agents displayed on the screen. At the beginning of each round of the game, a 2×2 grid of four rooms would be shown, and the two agents were placed in two different rooms randomly. A player could see the

location of his agent, without knowing where his partner was. The goal of this game was to bring their agents to meet in the same room (see figure 1).

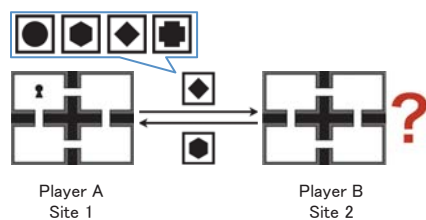


図 1 The coordination game.

For each round, each player could send a message to the partner by picking a figure from four options, whose order was different among players. After that, the players can choose to move to an adjacent room or to stay in the same room, whereas diagonal movements were prohibited. After they selected where to go, the outcome of that round would be presented. A whole game included multiple rounds. The above process of one round was repeated until the end of the game.

Similar with other coordination games, the players needed to act cooperatively to succeed in this game. To achieve that, they had to understand the meaning of others' messages. Crucially, as there were four options and four rooms, the players were encouraged implicitly to denote each room by a different figure. Meanwhile, all four figures were symmetrical, and the order of the options was different among players and hence could not convey meanings. Therefore, the use of preexisting communicative convention to form the room-message associations was highly impossible.

2.2 Subjects

Forty individuals, i.e., twenty pairs of participants (all male, mean age = 22.1, $SD = 2.3$ years old) were recruited to participate in our experiment. All subjects were right-handed. The individuals belonging to the same pairs were recruited separately and had never met with each other until the end of the experiment.

2.3 Procedure

All participants were instructed to go through two types of games in our experiment, the *single game (SG)* and the *communication game (CG)*. These two games shared similar procedures but with different goals.

At first, the participants had to finish the SG separately. In SG, the participants were asked to play the coordination game against a computer program. Although this game included message exchange and room movements, the messages and movements were randomly generated by a computer program. Hence, forming consistent associations between rooms and messages was impracticable. Instead of interpreting the “messages” as locations, the participants were given two kinds of tasks, the *judgment* task and the *matching* task. In either task, the participants had to remember the received messages. These tasks were designed to make sure that the participants had a cognitive load comparable with that in the CG. There were 48 rounds of game in the SG.

After both players in a pair finished the SG, they moved on to the CG, in which they played the coordination game together. Regardless of how well they performed, the CG lasted for 60 rounds for all pairs.

In both SG and CG, before the start of each round, there was a fixation cross displayed on the monitor for 2 s. This event was referred to as the *fixation* event. When a message was received in both games, the received message was displayed to the receiver for 3 s, during which the participants were instructed to sit passively and observe the received message. These events in SG and CG were referred to as the *receiving SG* event and the *receiving CG* event, respectively. These events were used for later analysis.

To evaluate the MNS activity, we calculate the mean power in the mu frequency (8-13 Hz) over sensorimotor cortex. Since participants were right-handed and the instruction of this experiment involved right-hand actions exclusively, we focus on the mu suppression which is related to right-hand movements only. Hence, only the data collected from the electrode covering the left somatosensory area (i.e., C3 scalp location) was used for statistical analysis. The results are demonstrated in the next section.

3. Results

In the CG, 16 pairs of participants (32 individuals) obtained an overall successful rate above 50% (mean successful rate = .728, $SD = .126$), which means that they had been able to meet in the same room for at least 30 rounds out of the total 60 rounds of the game. On the other hand, other four pairs of participants (8 individuals) performed no better than the chance level (mean successful rate = .213, $SD = .016$; expectation rate = .222). As these two groups of participants performed significantly differently in the game ($t(18) = 7.997, p < .001$), we contrasted the data of one group with the other group. In later analysis, these two groups of participants are referred as *successful group* and *failure group*, respectively.

In order to evaluate mu suppression at each event, we firstly computed the mu band power at the *fixation* events averaged across the SG and CG, and used it as the baseline power. The mu suppression at an event was then evaluated as the log ratio of the power at that event relative to the baseline power. By doing so, significant mu band power suppression was found for the *receiving* events in both SG ($t(39) = 4.050, p < .001$) and CG ($t(39) = 5.052, p < .001$). No significant difference was found from the results between the SG and CG ($t(39) = 1.565, p = .126$).

To find out whether the mu suppression was consistent across the whole CG, we divided the CG into two equal stages, i.e., the first half and the second half, with each half was constituted by 30 rounds of the game. We contrasted the mu suppression in the first half with the second half, and found a significantly stronger mu suppression in the first half than in the second half for the successful group ($t(31) = 4.261, p < .001$). In contrast, no such activity pattern was found for the failure group when comparing the mu suppression in each half of the game ($t(7) = 1.582, p = .158$). This result is plotted in figure 2.

4. Discussion

There are several ways to explain the observed mu suppression in this experiment. Firstly, our results may be affected by the posterior alpha activity, which overlaps with mu rhythms in frequency. Functionally different from mu rhythms, posterior alpha activity is

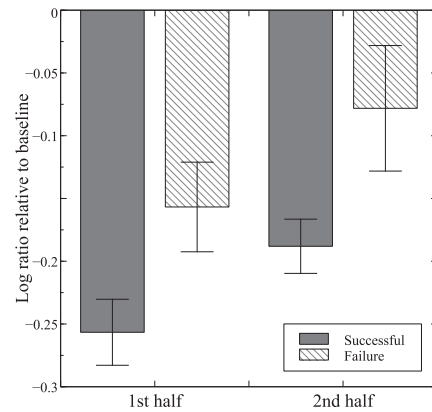


図 2 The mu suppression in different stages of the CG. Error bar is SEM.

known to reflect visual processing in neural networks of brain regions in occipital cortex, and is related to eye openness and attentiveness [18, 11]. However, as the baseline power used here was computed from the EEG data when the participants observed a fixation cross, the observed mu suppression can not be related to eye openness. Furthermore, the same visual stimuli and equal attention effects should be involved across the whole CG, thus can not be responsible for the stronger mu suppression in the first half of the game found in successful group.

Secondly, mu suppression had been found to be related to motor imagery [17]. In our experiment, observing a received message was always followed by a button response, which may lead to the imagery of the button pressing action when receiving messages from the partner. In addition, for those who performed well in the CG, the room referred to by received messages could be easily interpreted, which may lead to a motor imagery of a kind of virtual “movement” from one’s initial room to the room referred. This may help to explain the absence of the stronger mu suppression in the failure group, which may be related to the difficulty in interpreting the referent of the received messages. However, both the imagery of button pressing and the virtual “movement” should be the same across the whole CG for the successful group. Therefore, the stronger mu suppression found in the first half of the CG for the successful group needs a different explanation, which may be linked to the MNS-based simulation.

The core property of the MNS is, that it is active both when one observes and performs an action [21]. These perception-action mechanisms have been thought to allow “simulation” of a perceived action within the observer’s own brain as if the observer was performing the action him/herself. In this way, understanding of another mind is immediately available through understanding of one’s own mind [19]. This simulation mechanism had been considered to be probably at the basis of various and important aspects of social cognition, including attribution of mental states to others, and language [8].

Probably, the MNS was involved in our experiment in a similar way. That is, those who performed well in the game may interpret the meaning of a received message by simulating how themselves would mean when sending the same message. It may be this MNS-based “simulation” engendered an extra mu suppression over the sensorimotor cortex. Accordingly, the reason for performing poorly in the CG may be attributed to the absence of such a simulation process, which resulted in the same level of mu suppression across the whole game.

On the other hand, the stronger mu suppression was observed in the first half of the CG but not in the second half. It is probably that the simulation mechanism only existed within the formation process of the communication systems when it was necessary to share self own symbolic system with the other people. In the second half of the CG, the communication systems had been formed successfully, thus the messages could be understood without simulation, and hence the related mu suppression disappeared. If this is the case, the MNS may not be always necessary for symbolic communication. Future work is needed to clarify this point.

In conclusion, the results of this study suggest a possible involvement of a MNS-based simulation mechanism in the formation process of symbolic communication systems. Although this simulation mechanism may not be necessary for symbolic communication, it may benefit the symbolic communication at the forming stage.

Acknowledgment

We would like to thank Kazuyuki Samejima and Junya Morita for their helpful advices. This research was supported by a MEXT KAKENHI on Innovative Areas Grant Number 21120011 in 4103 and JSPS KAKENHI Grant Number 26240037.

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