Doctoral Thesis

Hemodynamics during motor imagery of self-feeding with chopsticks

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CONTENTS

ABBREVIATIONS

MI, motor imagery
NIRS, near-infrared spectroscopy
ME, motor execution
PFC, prefrontal cortex
SMC, sensorimotor cortex
ADLs, activities of daily living
VAS, visual analogue scale
oxy-Hb, oxygenated haemoglobin
deoxy-Hb, deoxygenated haemoglobin
Pre-SMA(PreSMA), pre-supplementary motor area
SMA, supplementary motor area
PMA, pre-motor area
ANOVA, repeated measures analysis of variance
MP, mental practice
ROIs, regions of interests

CHAPTER 1
GENERAL INTRODUCTION

Recently, neuroimaging technology has been greatly advanced, and human cerebral activities and connectivity during various tasks have been cleared using the system such as magnetic resonance imaging (MRI), transcranial magnetic stimulation (TMS), electroencephalogram, and near-infrared spectroscopy (NIRS). With these developments, new therapeutic theories and techniques in clinical scenarios also have been developed.

Among these, “motor imagery” (MI) is considered to be useful for motor rehabilitation. MI causes intermanual transfer (Amemiya et al., 2010), enhances motor performance (Blefari et al., 2015; Schuster et al., 2009; Seebacher et al., 2015; Beinert et al., 2015; Oostra et al., 2015; Kumar et al., 2016), causes motor learning (Jackson et al., 2001). Furthermore, MI can be also combined with brain computer interface (Neuper et al., 2009; Schurholz et al., 2012; Park et al., 2015; Kasahara et al., 2015), neuro-feedback (Blefari et al., 2015; Mihara et al., 2012 and 2013; Auer et al., 2016). And these combined systems can improve performance of patients who got cerebral damages (Fazli et al., 2012).

The application of repetitive MI is called mental practice (MP) in clinical scenarios. MP confers similar performance improvements as physical practice (Kappes et al., 2016). It is now a well-accepted about MI that near-identical brain areas are activated during motor execution (ME) and MI (Jeannerod, 1995; Decety, 1996; Wriessnegger et al., 2008; Wang et al., 2014). Also, a meta-analysis of activation-likelihood estimation suggested that MI relies on a network involving motor-related regions, including the pre-motor area (PMA), supplementary motor area (SMA), parietal lobule, cerebellum, and basal ganglion, which supports the view that ME and MI are very similar processes (Hetu et al., 2013). However, methodologies of MP using MI have not been well established, and these application methods are in too variety. As the importance of standardizing methodology was highlighted in a systematic review (Guerra et al., 2017). For the reasons why, we refer to the basic knowledge of MP as use of MI in this thesis.

In previous studies, many studies have already reported that near-identical brain areas were activated during ME and MI (Jeannerod, 1995; Decety, 1996; Wriessnegger et al., 2008; Wang et al., 2014). On the other hand, in rehabilitation setting, we need to consider about patients’ handedness when we address hand-related motor rehabilitation. For example, self-feeding with chopsticks are difficult to execute with the non-dominant hand. On the occasion of applying complex MI tasks for MP, if the MI ability is also affected by handedness, the hemodynamics during MI of the task might be different between the dominant and non-dominant hand. Additionally, MI vividness might also differ between hands; indeed, previous studies have suggested that cerebral activity can differ according to

MI vividness (Williams et al. 2012).

Considering these facts, we hypothesized as follows: 1) near-identical brain areas are activated during ME and MI of self-feeding with chopsticks, and there would be differences in 2) cerebral hemodynamics and 3) MI vividness during MI of self-feeding with chopsticks between the dominant and non-dominant hand. To address this hypothesis, we carried out the experiments with healthy subjects. As the conclusions from previous MI studies using NIRS, the activation of pre-supplementary motor area (Pre-SMA), SMA, prefrontal cortex (PFC), PMA and sensorimotor cortex (SMC), which are all in motor-related areas can be detected (Iso et al., 2016; Amemiya et al., 2010; Wriessnegger et al., 2008) and activated. Thus, NIRS was used as the main experimental technique in the present study, and assessment of cerebral activation will be outlined in the following sections of this chapter.

1-1. MOTOR IMAGERY AND MENTAL PRACTICE

MI can be defined as a dynamic state during which a subject mentally simulates a given action without any overt movements (Decety 1996; Blefari et al. 2015). MP, executed by repetitive MI, aims to improve motor performances without any simultaneous sensory input or overt output (Decety and Ingvar, 1990). MP can complement physical exercise because it can be undertaken by patients who are in acute recovery, wherein they cannot conduct ME due to reduced voluntary movement post injury. Moreover, MP can be executed safely anywhere and has been shown to improve upper limb function after stroke (Park et al., 2018). In addition, a combination of MP and physical practice can improve motor performance more than with physical practice alone (Wriessnegger et al. 2014).

The effects of MP have been demonstrated by many studies that compared cerebral activity during ME and MI, and have reported that near-identical brain areas were activated during ME and MI (Jeannerod, 1995; Decety, 1996; Wriessnegger et al., 2008; Wang et al., 2014). Also, in a TMS study, the motor-evoked potential, which is indicative of cortico-spinal excitability, was significantly larger during MI than during rest (Roosink et al. 2010; Feurra et al. 2011). Moreover, a previous functional MRI study suggested that nearly the same cerebellar areas are activated during ME and MI of activities that require the use of tools, despite the activation differences among tasks (Higuchi et al. 2007). A meta-analysis of activation-likelihood estimation suggested that MI relies on a network involving motor-related regions, including the PMA, the SMA, parietal lobule, cerebellum, and basal ganglion, which supports the view that ME and MI are very similar processes (Hetu et al., 2013).

1-2. NEAR-INFRARED SPECTROSCOPY

NIRS is non-invasive and easy to use, and its reliability and replicability have been demonstrated previously (Kono et al. 2007; Maslehaty et al. 2012; Iso et al. 2016). It can detect changes of cerebral oxygenation while subjects are performing tasks, even in clinical scenarios. The ETG-4000 system (Hitachi Medical Co., Tokyo, Japan) with 24 channels, which consisted of 4*4 optode probe sets (8 emitters and 8 detectors) can record haemoglobin levels. The detected haemoglobin levels were converted to changes in oxygenated haemoglobin (oxy-Hb), deoxygenated haemoglobin (deoxy-Hb), and total haemoglobin levels based on the modified Beer–Lambert approach (Cope et al. 1988; Obrig et al. 2003).

Each probe is placed 3.0 cm away from the other probes (Fig 1). Also, the present system used two wavelengths of near-infrared light, which were approximately 625 and 830 nm, and the reflected light was sampled at 10 Hz. This system estimates changes in oxy-Hb levels at a depth of 3.0 cm below the scalp (Fig 2).

1-3. SUMMARY OF THE AIM OF THIS THESIS

Although many researchs have been revealing about cerebral activation during MI, most of these reports used simple tasks; only a few reports, to date, have used complex tasks, such as activities of daily living (ADLs), that are essential in clinical scenarios in rehabilitation medicine.

A thorough understanding of cerebral hemodynamics during MI of complex movements is essential to develop the use of MP in relevant clinical scenarios. For example, cerebral hemodynamics during MI of the self-feeding activity task, one of the ADLs, remain unclear. We selected self-feeding as the MI task because it is frequently used for stroke patients undergoing rehabilitation, and it is a complex activity that engages various movements, including arm and finger movements, chewing and swallowing, and using cutlery (e.g., chopsticks). Therefore, MP with MI of self-feeding could be beneficial for patients with dominant-hand hemiplegia.

Thus, our main objective was to use NIRS to investigate the cerebral hemodynamics associated with the MI of a self-feeding activity with chopsticks. The aim of each chapter is as follows: Chapter 2 was to investigate the cerebral hemodynamics associated with the MI and ME of a self-feeding activity with chopsticks. The aim of Chapter 3 was to investigate differences in cerebral hemodynamics during MI of self-feeding with chopsticks using the dominant or non-dominant hand. Our findings provide basic knowledge for the use of MI in ADLs in clinical scenarios.

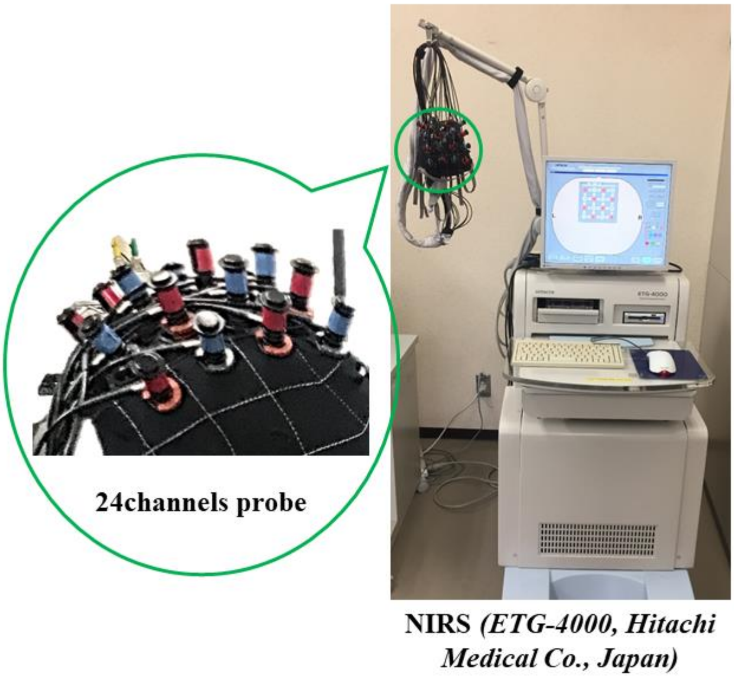

Figure 1. The ETG-4000 system (Hitachi Medical Co., Tokyo, Japan) with 24 channels
24 channels consisted of 4*4 optode probe sets (8 emitters and 8 detectors). Each probe is placed 3.0 cm away from the other probes.

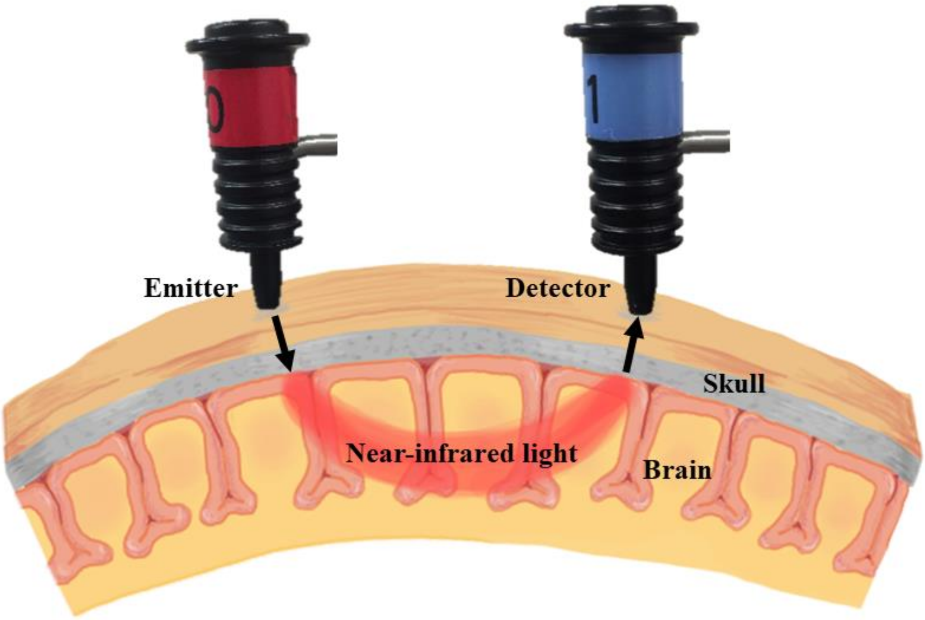

Figure 2. The present system used two wavelengths of near-infrared light
The near-infrared lights are approximately 625 and 830 nm, and the reflected light was sampled at 10 Hz. This system estimates changes in oxy-Hb levels at a depth of 3.0 cm below the scalp, and can record changes in oxy-Hb, deoxy-Hb, and total haemoglobin levels. oxy-Hb, oxygenated haemoglobin; deoxy-Hb, deoxygenated haemoglobin.

CHAPTER 2
HEMODYNAMIC COMPARISON BETWEEN MOTOR EXECUTION AND MOTOR IMAGERY OF SELF-FEEDING ACTIVITY

2-1. INTRODUCTION

MI is an act wherein an individual contemplates mental action of ME without obvious action (Decety, 1996; Blefari et al., 2015). MP, executed by repetitive MI, aims to improve motor performances without any simultaneous sensory input or overt output (Decety and Ingvar, 1990). MP can complement physical exercise because it can be undertaken by patients who are in acute recovery, wherein they cannot conduct ME due to reduced voluntary movement post injury. Moreover, MP can be executed safely anywhere and has been shown to improve upper limb function after stroke (Park et al., 2018). In addition, a combination of MP and physical practice can improve motor performance more than with physical practice alone (Wriessnegger et al. 2014).

The effects of MP have been demonstrated by many studies that compared cerebral activity during ME and MI, and have reported that near-identical brain areas were activated during ME and MI (Jeannerod, 1995; Decety, 1996; Wriessnegger et al., 2008; Wang et al., 2014). A meta-analysis of activation-likelihood estimation suggested that MI relies on a network involving motor-related regions, including the PMA, SMA, parietal lobule, cerebellum, and basal ganglion, which supports the view that ME and MI are very similar processes (Hetu et al., 2013). However, most of these reports used simple movements as tasks; only a few reports, to date, have used complex movements that are essential in clinical scenarios in rehabilitation medicine.

A thorough understanding of cerebral hemodynamics during MI of complex movements is essential to develop the use of MP in relevant clinical scenarios. Cerebral hemodynamics during MI of the self-feeding activity task, one of the ADLs, remain unclear. We selected self-feeding as the MI task because it is frequently used for stroke patients undergoing rehabilitation, and it is a complex activity that engages various movements, including arm and finger movements, chewing and swallowing, and using cutlery (e.g., chopsticks). Therefore, MP with MI of self-feeding could be beneficial for patients with dominant-hand hemiplegia.

Among the previous studies involving tool-use MI, a functional magnetic resonance imaging-based assessment indicated that near-identical cerebral regions were excited with either tool-use ME or MI, although differences in excitability were observed (Higuchi et al., 2007). However, a research study of NIRS suggested that tool-use MI task can significantly increase oxy-Hb levels in motor-related cerebral areas than MI tasks undertaken without tool-use (Oikawa et al., 2017). Thus, our main objective was to investigate the cerebral hemodynamics associated with the MI and ME of a self-feeding activity with chopsticks.

2-2. MATERIALS AND METHODS

2-2-1. Subjects

We included 21 right-handed volunteers (14 females, 7 males; age: 29.4 ± 10.2 years) in the present study. The right-handedness of participants was confirmed by the Edinburgh Handedness Inventory (Oldfield, 1971). All prospective participants were explained the safety regulations of this research work and assured that none of their identifying information would be disclosed; thereafter, all participants provided written informed consent for study participation. We obtained additional informed consent from all individual subjects whose identifiable information was included in this study. None of the study participants had a history of major physical disorders, including neurological illness, brain injury, or psychiatric illnesses. This research was approved by the Nagasaki University ethical review committee and conformed to the principles of the Declaration of Helsinki (World Medical Association, 2013) and its later amendments.

2-2-2. Experimental Protocol

2-2-2-1. Task

The study task was for participants to eat sliced cucumber pickles with the right hand by using chopsticks and included reaching to the mouth, chewing, and then swallowing. Participants were asked to execute serial movements of the task within 20 seconds. These tasks were conducted under ME and MI conditions.

All participants practiced each task before the experimental session until they could undertake the tasks sufficiently well during the experiment. The participants checked the actual slices of cucumber pickles on a dish with chopsticks, and repeated the task practice while monitoring the time required to perform it by using a stopwatch.

2-2-2-2. Experimental Setup

The participants sat on a chair with a backrest in a silent room. They placed their forearms in an intermediate and relaxed position on the table and were instructed to carry out the actual self-feeding activity with their eyes open during the ME condition, and to imagine the task with their eyes closed without other movements during the MI condition. Moreover, they were instructed not to move their head, to maintain the same posture as much as possible, and to not speak during both conditions throughout the experiment. In addition, they were asked to maintain the same posture and relax without thinking for the remainder of the session.

After the MI task, the visual analog scale was used to investigate MI vividness, which has been previously described (Lotze et al. 2003 and 2006; Malouin et al. 2008; Ikeda et al. 2012). All participants assessed the vividness of the MI task, which they marked on the visual analog scale: range from 0 to 100 mm (0%; none, 100%; very vivid).

2-2-2-3. NIRS Measurements

We investigated cerebral activation using the NIRS, which has been previously applied in clinical scenarios. We recorded the levels of oxy-Hb, deoxygenated hemoglobin, and total hemoglobin with the 24-channel ETG-4000 (Hitachi Medical Co., Tokyo, Japan); the device has 8 emitters and detectors, and comprises 4*4 probe sets. Every probe was positioned 3 cm away from each other and placed in accordance with the international 10–20 electroencephalography placement method (Okamoto et al., 2004). Then, Cz was marked as a reproducible marker in the probes, as described previously (Figure 3) (Okamoto et al., 2004; Saimpont et al., 2015).

We proceeded to examine 8 ROIs: the Pre-SMA, SMA, the bilateral PFC, PMA, and SMC; Fig 3. The activation of the Pre-SMA, SMA, and left and right PFC (L-PFC/R-PFC) were detected by channels 2, 5, 6, and 9; channels 9, 12, 13, and 16; channels 1 and 4; and channels 3 and 7, respectively. The activations of the left and right PMA (L-PMA/R-PMA) were detected by channels 8, 11, and 15 and by channels 10, 14, 17, respectively, whereas the activations of the left and right SMC (L-SMC/R-SMC) were detected by channels 18 and 22, and by channels 21 and 24, respectively (Hatakenaka et al., 2007; Sagari et al., 2015; Iso et al., 2016; Matsuo et al., 2019). The levels of oxy-Hb and deoxygenated hemoglobin were calculated from the levels of hemoglobin detected by using the modified Beer–Lambert approach (Cope and Delpy, 1988; Obrig and Villringer, 2003).

After completion of the task practice session, NIRS measurements were taken with three cycles of 20-s task and 30-s rest in a blocked design (Fig. 4) that has been described previously (Iso et al., 2016; Matsuo et al., 2019). The blocked design was used in each condition; thus, there were three cycles of the task each in MI and ME condition. All participants were assessed under each condition, with the condition order (ME or MI) equilibrated. The study participants were instructed to execute or imagine eating a pickle once for a 20-s duration. In the MI condition, the participants were instructed to imagine they were eating the pickle. Thus, the research involved the participants imagining a first-person view with kinesthetic imagery, which included sounds. The timing of the task or rest was indicated by the words “start” or “stop”, spoken by the examiner.

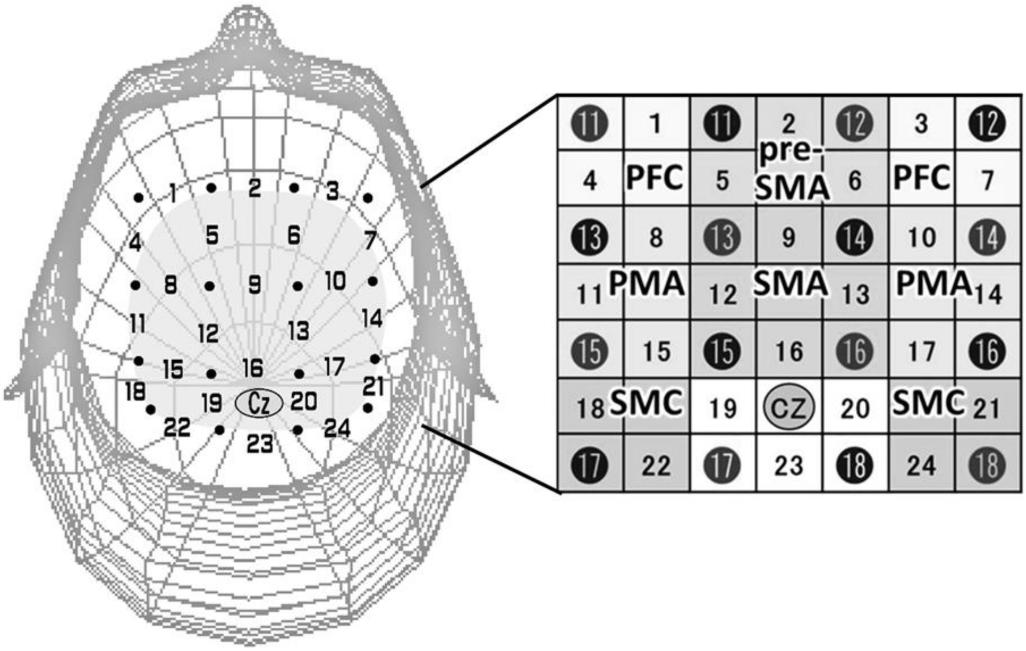

Figure 3. NIRS Probe Sets

The NIRS probes were placed in the similar way of the international 10–20 electroencephalography placement method. The Cz was marked as a replicable point in the probes. The Pre-SMA, SMA, PFC, PMA, and SMC were examined. NIRS, near-infrared spectroscopy; Pre-SMA, pre-supplementary motor area; SMA, supplementary motor area; PFC, prefrontal cortex; PMA, pre-motor area; SMC, supplementary motor cortex

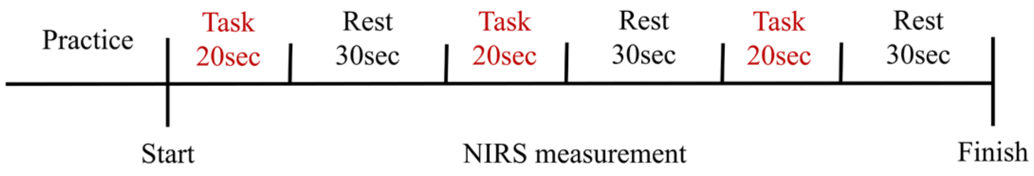

Figure 4. Experimental Protocol

The experiment was performed with a blocked design consisted from three cycles of the 20 s task and the 30 s rest. The task practice session was finished before the NIRS measurements were started. NIRS, near-infrared spectroscopy.

2-2-2-4. Data Analysis

In this study, changes in the concentration of oxy-Hb were used to indicate brain activation during tasks, because oxy-Hb is the most sensitive parameter for detecting cerebral activity (Hoshi et al., 2001). We used the 5-s moving average method to exclude short-period motion artifacts from the analyzed data, and analyzed the data using the integral mode to calculate average values.

For data analysis, we considered the 5 s before the task as the pre-task baseline, and the 5 s after the task was completed as the post-task baseline; thereafter, we applied linear fitting to the data between these baselines. Moreover, we excluded the first 5 s of tasks from the analyses to ensure the data were unaffected by the time required for cerebral activation to occur. Thus, we included the last 5 to 20 s of the task duration for analyses (Fig. 5). Next, we calculated data from three cycles with the signal-averaging technique. The 3-Hz high-pass filter of the wave analysis marked channels that included high noise levels to exclude noise such as hyperactivation caused by skin and blood dynamics (Takahashi et al., 2011). In addition, surface electromyography was applied to ensure that participants did not move during the MI condition. The surface electromyography electrodes were positioned over the right masseter and the first dorsal interosseous muscles of the right hand, and signals were amplified and filtered at 5 to 3 kHz of bandwidth with the Neuropack Sigma MEB-5504 digital signal processor (Nihon Kohden, Tokyo, Japan). An A/D converter transferred the signals to a PC for offline analysis (PowerLab16/30, AD Instruments, Sydney, Australia). During surface electromyography measurements, we ensured that the finger and face postures of all participants were immobile, without overt muscle movement. Therefore, all the data were used for analyses.

2-2-2-5. Statistical Analysis

The mean oxy-Hb levels during the ME and MI conditions were calculated, and data were converted to the Z-score. We obtained mean 0 and up to 1 standard deviation (Tsunashima and Yanagisawa, 2009), through calculations undertake in the ETG-4000. The two-way repeated measures analysis of variance (ANOVA) was used for “ROIs” (Pre-SMA, SMA, L- and R-PFC, L- and R-PMA, as well as L- and R-SMC) and “conditions” (ME and MI) as factors to compare differences in the Z-scores. Furthermore, the Z-scores were compared by the Bonferroni test. We used the Statistical Package for the Social Sciences (22.0 ver., IBM, Tokyo, Japan) for data analysis. P-value <0.05 was considered statistically significant.

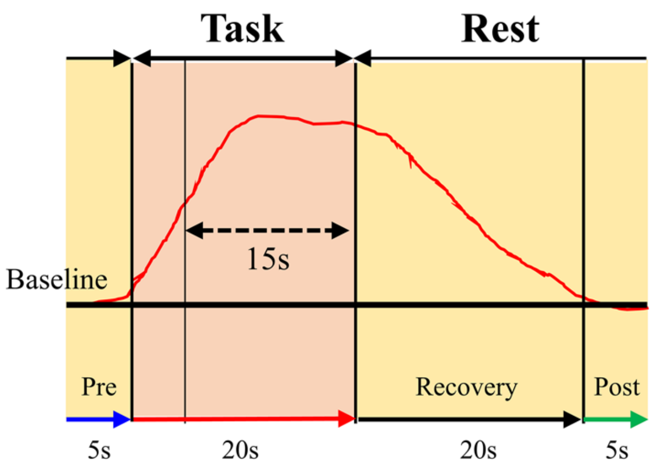

Figure 5. Method of Calculating Oxy-Hb Changes

Linear fitting was used to the periods of the pre-task (blue arrow) to post-task (green arrow). The pink background is the task duration, and the skin color background is the rest duration. The vertical axis indicates the oxy-Hb levels (mMmm), and the horizontal axis indicates the time of one cycle. The first 5 s of the tasks were excluded, and the final 5 to 20 s of the task duration were used for the analyses.

2-3. RESULTS

The mean ± SD Edinburgh Handedness Inventory score of all participants was 88.6 ± 12.0; in addition, 76% of participants answered “always using the dominant hand” to the question relevant to self-feeding. Furthermore, none of the participants answered, “always using the non-dominant hand”. All participants self-reported that they have used chopsticks with their dominant hand nearly every day for approximately 20 years or more, indicating that they had a proficient level of skill in using chopsticks. Moreover, the mean visual analog scale value (vividness of the MI task) of all participants was 73.1 ± 10.4mm.

Figure 6 shows the grand average waveforms of oxy-Hb during tasks for all subjects. During tasks, the oxy-Hb levels increased over the baseline value in most ROIs. The significant main effect of “ROIs” [$F(7,14) = 4.918$, $P = 0.000$, $\eta 2 = 0.193$], and a significant “ROIs *conditions” interaction [$F(7,14) = 2.221$, $P=0.036$, $\eta 2 = 0.114$] were revealed by two-way ANOVA, whereas there was no main effect of “conditions” [$F(1,20) = 0.002$, $P=0.968$, $\eta 2=0.000$]. Based on the main effect of ROI and interaction of ROI*conditions, we assessed Z-score differences with the Bonferroni test, and found the Z-score during ME were significantly higher in the L-SMC than in the SMA ($P = 0.033$) and the L-PMA ($P = 0.039$), whereas there were no apparent differences between ROIs during the MI. Furthermore, significantly higher oxy-Hb levels were detected in the SMA ($P = 0.017$) and the L-PMA ($P = 0.012$) during MI, in contrast to the levels that were observed during the ME; however, there were no apparent differences in the other ROIs (Figure 7).

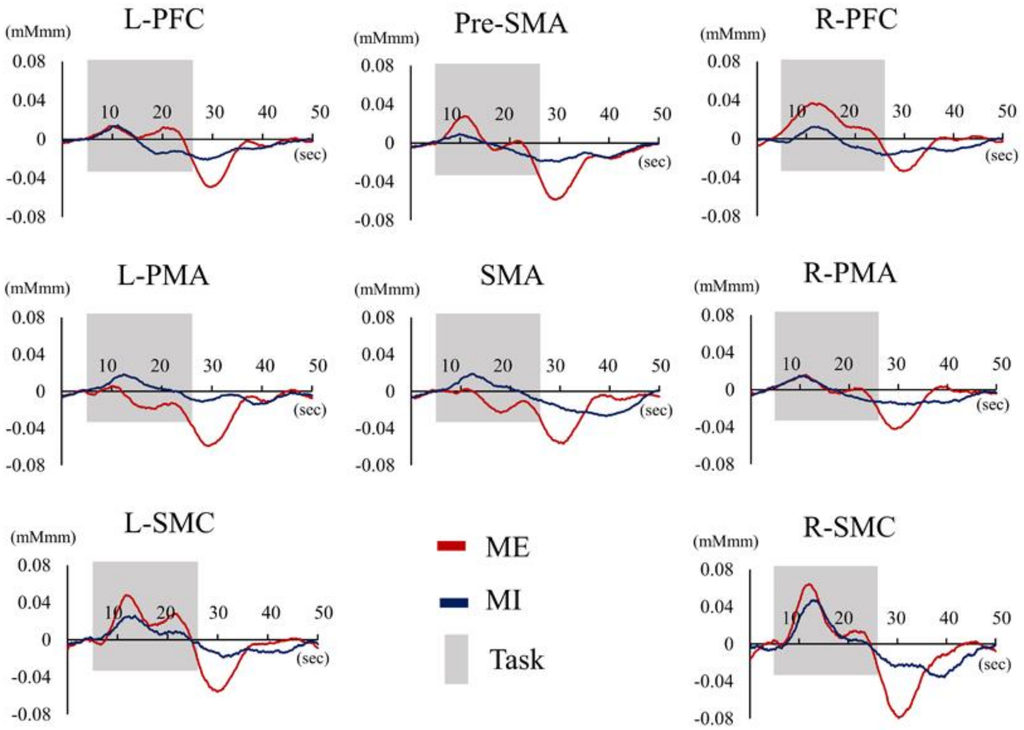

Figure 6. Oxy-Hb Time Course

The all subjects' grand average wave forms of oxy-Hb during tasks are shown. The blue line is oxy-Hb levels of the MI condition, and the red line is oxy-Hb levels of the ME condition. The gray background is the task duration (5–25 seconds), and the white background indicates the rest duration (25–50 and 0–5 seconds). MI, motor imagery; ME, motor execution; Pre-SMA, pre-supplementary motor area; SMA, supplementary motor area; PFC, prefrontal cortex; PMA, pre-motor area; SMC, supplementary motor cortex.

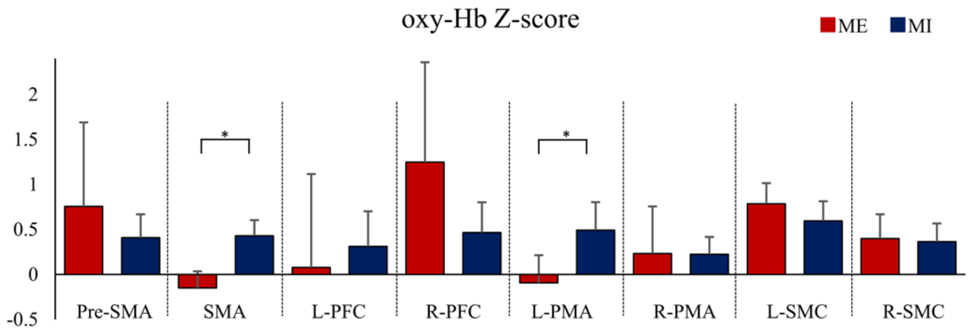

Figure 7. Comparison of the Cerebral Hemodynamics between Conditions

The oxy-Hb signal data were analyzed using two-way ANOVA with the Bonferroni test. The blue line is the oxy-Hb Z-score of the MI condition, while the red line is the oxy-Hb Z-score of the ME condition. The oxy-Hb levels were significantly higher during MI than during ME in the SMA and the L-PMA. ANOVA, repeated measures analysis of variance; MI, motor imagery; ME, motor execution; Pre-SMA, pre-supplementary motor area; SMA, supplementary motor area; PFC, prefrontal cortex; PMA, pre-motor area; SMC, supplementary motor cortex.

2-4. DISCUSSION

In this study, we investigated the cerebral hemodynamics during ME and MI of a self-feeding activity with chopsticks by using NIRS. A previous study using a simple finger-tapping task suggested that increases in oxy-Hb levels in the SMA and PMA during MI were similar to those observed during ME (Iso et al., 2016), although another study that uses the same task suggested that the PFC was more activated during MI than during ME, whereas the left SMA was more activated during ME than MI (Wu et al., 2018). Furthermore, an fMRI study suggested that stronger cerebral activations were observed in the PMA and the SMA during ME than during MI of swallowing, which is a simple task (Kober et al., 2019). As such, many previous MI studies using simple tasks have suggested that near-identical brain areas are activated during MI and ME, although the brain areas were more activated during ME than during MI. However, our results suggested that, although MI and ME of self-feeding activity as a tool-use complex task activated mostly overlapping cerebral areas, these activations were not identical, with MI inducing higher activation levels in some areas compared to ME. The Z-scores during ME were significantly higher in the L-SMC than in the SMA and the L-PMA. Moreover, cerebral activation differences were observed between ME and MI conditions, with significantly higher oxy-Hb levels detected during the MI condition than the ME condition in the SMA and the L-PMA; these results were not identical to those reported with simple MI tasks.

The SMA and PMA are known to play roles in motor planning, motor preparation, and motor learning (Hoshi et al., 2004; Nakayama et al., 2008; Wang et al., 2016). MI is equivalent to the motor planning and preparation for ME (Tong et al., 2017). A previous study suggested that SMA activation was mainly observed in MI, with partially overlapping activation during ME and MI (Stephan et al., 1995). Moreover, other studies suggested that SMA activation affected the inhibition of the SMC during MI (Gao et al., 2014; Di Rienzo et al., 2014). Some neurons of the PMA may be solely involved in the MI task (Raffin et al., 2012); the PMA serves as a hub that connects cognition and motor activities (Hanakawa, 2011). Both SMA and PMA activation during ME and MI are affected by the task experiences and the task-proficiency levels; moreover, they are dependent on the task specificity and are changeable by the degree of practice. Thus, low activity may indicate low nerve-activation levels; however, low activity can also imply better task proficiency (Debarnot et al., 2014).

The self-feeding activity using chopsticks with the right hand, which was used in the present study, was familiar to all participants because they had been executing the task nearly every day for at least 20 years. Thus, the task was easy for them and they could carry it out expertly and did not need to intentionally implement the cognitive process. Thus, SMA and PMA activation might have been reduced during ME, and the differences in the SMA and PMA activation between ME and MI might be related to a need for intentional cognitive processes. Overall, our results further expand the knowledge with regard to MI and may be useful in developing MP in rehabilitative fields.

2-4-1. Research limitations

The subjects were all right-handed volunteers who were skilled in the use of chopsticks; therefore, it is unclear whether our results can be generalizable to individuals unskilled in the use of chopsticks, left-handed people, or patients with motor diseases or disabilities. Furthermore, the task was limited to a self-feeding activity; thus, it is unclear whether cerebral hemodynamics during other complex tasks are similar to those observed during the self-feeding activity. In addition, our study only included a small number of participants. Because of these limitations, future studies should include more subjects with various conditions for MP, as well as left-handed subjects, and investigate cerebral activation during various tasks, including other complex tasks to confirm the effectiveness of MP in rehabilitation.

2-4-2. Conclusion

Levels of cerebral activation differed in some areas during ME and MI of a self-feeding activity. SMA and PMA have important roles in the MI of self-feeding activity. Furthermore, levels of activation in the SMA and PMA during ME and MI were affected by the necessity of intentional cognitive processes. Our findings expand the knowledge base of MI, and provides further understanding of the use of MI in rehabilitation for activities of daily living. Therefore, this study might contribute to the application of MP in clinical situations.

CHAPTER 3
CEREBRAL HAEMODYNAMICS DURING MOTOR IMAGERY OF SELF-FEEDING WITH CHOPSTICKS: DIFFERENCES BETWEEN DOMINANT AND NON-DOMINANT HAND

3-1. INTRODUCTION

MI can be defined as a dynamic state during which a subject mentally simulates a given action without any overt movements (Decety 1996; Blefari et al. 2015). With advances in neuroimaging systems, cortical activation during MI tasks can now be measured. For example, in a NIRS study, both ME and MI of hand-finger opposition tasks increased cerebral blood flow in almost all of the same areas, including the PFC, primary motor cortex, and SMC (Wriessnegger et al. 2008). Also, in a TMS study, the motor-evoked potential, which is indicative of cortico-spinal excitability, was significantly larger during MI than during rest (Roosink et al. 2010; Feurra et al. 2011). Moreover, a previous functional magnetic resonance imaging study suggested that nearly the same cerebellar areas are activated during ME and MI of activities that require the use of tools, despite the activation differences among tasks (Higuchi et al. 2007).

Many studies have investigated cerebral activation during MI of simple tasks, but only a few have focused on MI of complex tasks, such as ADLs, which are relevant clinically. Some ADLs are impacted by handedness. For example, self-feeding with chopsticks requires several types of movement, such as arm and finger movements, and the use of tools, which are difficult to execute with the non-dominant hand. Thus, if the MI ability is also affected by handedness, the haemodynamics during MI of self-feeding with chopsticks might be different between the dominant and non-dominant hand. Additionally, MI vividness might also differ between hands; indeed, previous studies have suggested that cerebral activity can differ according to MI vividness (Williams et al. 2012).

Hence, our hypotheses were as follows: there would be differences in 1) cerebral haemodynamics and 2) MI vividness during MI of self-feeding with chopsticks between the dominant and non-dominant hand. Thus, our aim was to use NIRS to investigate differences in cerebral haemodynamics during MI of self-feeding with chopsticks using the dominant or non-dominant hand. Our findings provide basic knowledge for the use of MI in ADLs in clinical scenarios.

3-2. MATERIALS AND METHODS

3-2-1. Subjects

Twenty healthy right-handed participants (14 women, 6 men; age: 26.9 ± 8.8 years) participated in this study. All participants were consistent right-handers according to the Edinburgh handedness inventory (Oldfield 1971). After being informed about the safety regulations for the study and acknowledging that they cannot be identified through this manuscript, all participants provided written informed consent for participation. No participants had a history of neurological illness, head injury, major physical illness, or psychiatric disorders. This study was conducted in the Biomedical Science Department of Nagasaki University. It was approved by the Nagasaki University ethical review committee and complied with the Declaration of Helsinki (World Medical Association 2001).

3-2-2. MI task

The MI task required that the participant imagine he or she is eating sliced cucumber pickles using chopsticks, including chopstick manipulation, bringing the pickle into the mouth, chewing, and swallowing. MI was performed in two conditions: one was MI with the dominant hand (dominant MI), and the other was MI with the non-dominant hand (non-dominant MI).

To decrease the variability in MI between participants, all participants completed a 5-min MI practice session with practice videos (Figure 8) before each task. The practice video represented the first-person view, which showed that the sliced cucumber pickles were in a dish on a table; the person picked up a pickle with the chopsticks and brought it to the mouth. The video was accompanied by the sound of pickles being eaten, which could be heard through earphones. The practice video length (from chopsticks manipulation to swallowing) was 10 s, which was the same as the length of the actual MI task. To ensure consistency between practice videos for the right and left hands, the video for the MI condition using the non-dominant hand was created by inverting the video of the dominant hand.

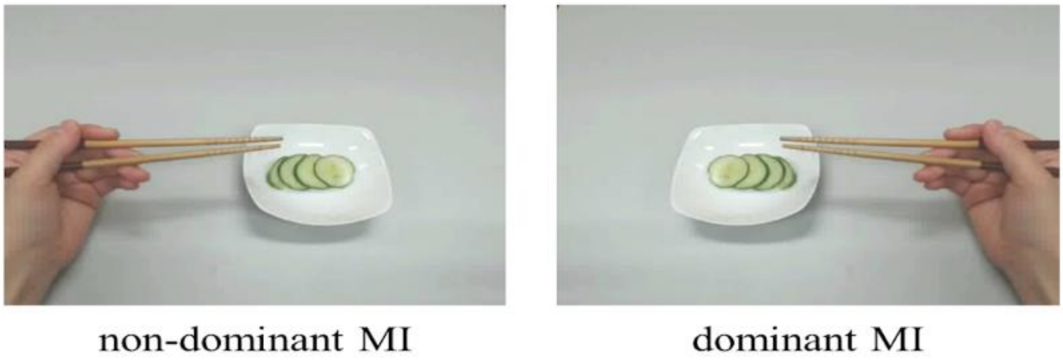

Figure 8. Still image of the MI practice video

The video represents the first-person view. One practice cycle (from chopstick manipulation to swallowing) was 10-s long, which was the same length as the actual MI task. The video for the non-dominant MI condition was created by inverting the dominant MI condition video. MI, motor imagery.

3-2-3. Experimental protocol

The participants sat on a comfortable chair in a quiet room. They were instructed to put their forearms in an intermediate position on the table, to relax, not to move their head or arms as much as possible, and not to speak during the experiment. After showing the MI practice videos, NIRS measurements were collected as part of a block design, which included three cycles of 20 s of the task and 30 s of rest (Figure 9), as in a previous study (Iso et al. 2016). This block design was consistent between the two conditions, comprising three cycles of the task (total 6 trials) in the dominant MI condition and another three cycles of the task (total 6 trials) in the non-dominant MI condition. All participants were examined in both conditions.

The condition order (dominant MI and non-dominant MI) was counter-balanced. The participants were asked to imagine eating pickles twice for 20 s and to imagine that they were actually doing it. Thus, they imagined kinaesthetic imagery, which included sounds, and were instructed not to move and to keep their eyes closed. Participants were instructed to maintain the same position and to relax without thinking during the rest period. They were notified when the task or rest session began by the words “start” or “stop,” announced by the researcher.

The visual analogue scale (VAS), which is used to assess subjective MI vividness (Lotze et al. 2003; Lotze et al. 2006; Malouin et al. 2008; Ikeda et al. 2012), was employed to investigate MI vividness after each MI task. The participants were asked how vividly they could imagine the MI task and were instructed to mark their responses on the VAS, which ranged from 0 mm (0%; none) to 100 mm (100%; very vivid).

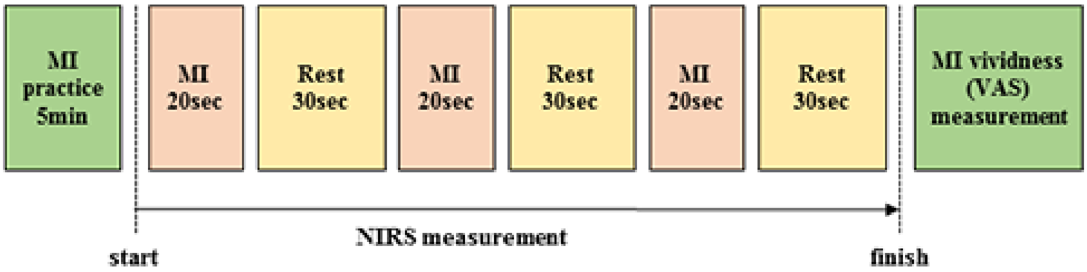

Figure 9. Experimental protocol

NIRS measurements were collected as part of a block design, which included three cycles of 20 s for the task and 30 s of rest. The 5-min MI practice session was completed before NIRS measurements were obtained, and MI vividness was measured by the VAS following the NIRS measurements. MI, motor imagery; NIRS, near-infrared spectroscopy; VAS, visual analogue scale.

3-2-4. NIRS measurements

NIRS is non-invasive and easy to use, and its reliability and replicability have been demonstrated previously (Kono et al. 2007; Maslehaty et al. 2012; Iso et al. 2016). It can detect changes of cerebral oxygenation while subjects are performing tasks, even in clinical scenarios. In this study, changes in oxy-Hb, deoxy-Hb, and total haemoglobin levels were recorded using the ETG-4000 system (Hitachi Medical Co., Tokyo, Japan) with 24 channels, which consisted of 4 × 4 optode probe sets (8 emitters and 8 detectors). Each probe was placed 3.0 cm away from the other probes. The NIRS channels were positioned according to the international 10–20 electroencephalography placement system (Okamoto et al. 2004), and Cz was positioned as a replicable marker of the probes, as determined by previous studies (Figure 10) (Okamoto et al. 2004; Saimpont et al. 2015). The present system used two wavelengths of near-infrared light, which were approximately 625 and 830 nm, and the reflected light was sampled at 10 Hz. This system estimates changes in oxy-Hb levels at a depth of 3.0 cm below the scalp.

Activation of the Pre-SMA, SMA, bilateral PFC, bilateral PMA, and bilateral SMC were assessed as the ROIs in this study (Figure 10). The activity level of the Pre-SMA was detected by channels 2, 5, and 6; that of the SMA by channels 9, 12, 13, and 16; of the left PFC (L-PFC) by channels 1 and 4; and of the right PFC (R-PFC) by channels 3 and 7. Moreover, the activity level of the left PMA (L-PMA) was detected by channels 8, 11, and 15; that of the right PMA (R-PMA) by channels 10, 14, and 17; of the left SMC (L-SMC) by channels 18 and 22; and of the right SMC (R-SMC) by channels 21 and 24 (Hatakenaka et al. 2007; Sagari et al. 2015; Iso et al. 2016).

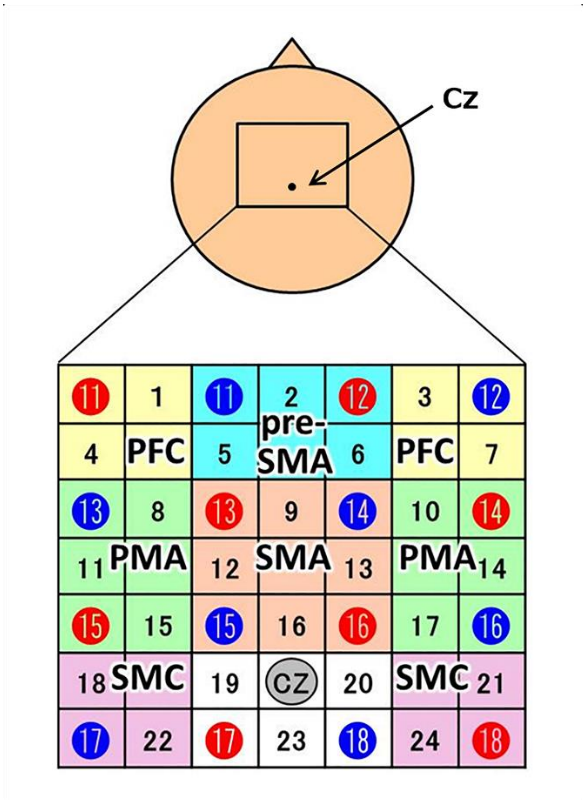

Figure 10. NIRS channel probe sets

NIRS channels were positioned according to the international 10–20 electroencephalography placement system, and the Cz electrode was positioned as a replicable marker of the probes. The SMC, PMA, PFC, PreSMA, and SMA were assessed as the ROIs. NIRS, near-infrared spectroscopy; PFC, prefrontal cortex; PMA, pre-motor area; PreSMA, pre-supplementary motor area; SMA, supplementary motor area; SMC, supplementary motor cortex.

The detected haemoglobin levels were converted to changes in oxy-Hb and deoxy-Hb levels based on the modified Beer–Lambert approach (Cope et al. 1988; Obrig et al. 2003). In this study, we used the mean oxy-Hb concentration changes and peak oxy-Hb timing to signify brain activation caused by the MI task, as oxy-Hb levels represent a sensitive parameter to detect brain activation (Hoshi et al. 2001). The moving average method (window: 5.0 s) was used to remove short-term motion artefacts from the analysed data. The obtained data were analysed using the integral mode, which calculates the average waveform from three cycles of data acquisition. We determined the pre-task baseline as the mean over the 5.0 s prior to the task period, and the post-task baseline as the mean over the last 5.0 s of the post-task period. We applied linear fitting to the data between these two baselines. The first 5.0 s of each task were excluded from the analyses to ensure that the data would not affected by the nerve–blood vessel coupling system, a phenomenon in which brain blood vessel ectasia and increased brain blood flow require time to occur. Thus, the last 5.0 to 20.0 s (total: 15.0 s) of the task period were used for analyses (Figure 11), and all data for the three cycles were calculated using the signal-averaging technique. Channels with high noise levels were marked using a high-pass filter at 3.0 Hz, which was 0.1 standard deviation above the wave analysis, so that it would not be affected by noise or hyperactivation due to skin blood flow (Takahashi et al. 2011). The mean, peak time, and standard deviation were examined for all participants.

3-2-5. Electromyography measurements

Surface electromyography (Neuropack Sigma MEB-5504, Nihon Kohden, Japan) was used to monitor the participants' muscles and to ensure that they did not move. The electromyography electrodes were positioned over three spots as follows: the left masseter muscle and the right and left first dorsal interosseous muscles, which are related to self-feeding activities. The electromyography frequency waves fluctuated between 5 Hz–3 kHz and were converted to digital data with a sampling rate of 2 kHz using an A/D conversion device (PowerLab16/30, AD Instruments, Australia). The electromyography measurements showed that the finger and face posture were unaltered in each participant, with no evidence of obvious muscle activation. Thus, all the participants' data were included in the analyses.

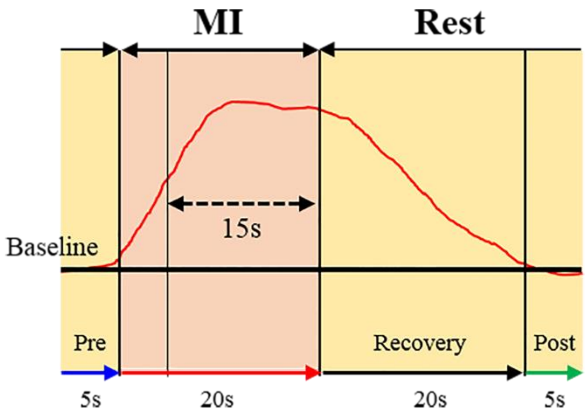

Figure 11. Method for calculating oxy-Hb changes

Linear fitting was applied to the data between pre-task (blue arrow) and post-task (green arrow) periods. The thick black arrow above the red curve indicates the MI period, and the thin arrow indicates the rest period. The vertical axis represents oxy-Hb concentration (mMmm), and the horizontal axis represents the time course of one cycle. The first 5 s of the MI tasks were excluded from the analyses. The final 5 to 20 s (total 15 s) of the task period were used for the analyses. MI, motor imagery; oxy-Hb, oxygenated haemoglobin.

3-2-6. Statistical analysis

VAS values, mean oxy-Hb values, and peak oxy-Hb time during the MI tasks were calculated for both conditions (dominant MI and non-dominant MI). The Wilcoxon's signed-rank test was used to examine differences in VAS values between the dominant MI and non-dominant MI conditions. Two-way ANOVA was performed with the "ROIs" (PreSMA, SMA, L-PFC, R-PFC, L-PMA, R-PMA, L-SMC, R-SMC) and "condition" (dominant MI, non-dominant MI) as within-subject factors, to examine oxy-Hb differences, both regarding the mean oxy-Hb values and peak oxy-Hb times. The peak times in all participants were compared using Bonferroni test, while effect sizes were calculated for the mean values and peak times. In addition, in order to reveal the haemodynamic correlations between ROIs, raw oxy-Hb data were converted to oxy-Hb z-score data, and the relationships among ROIs were determined. The z-score represents the value with a mean value of 0 and a standard deviation of 1 (Tsunashima et al. 2009). The z-score was automatically calculated for each participant using the ETG-4000 system. Next, Spearman's rank correlation was used to examine the relationship between cerebral haemodynamics and ROIs during MI. The statistical analysis software Statistical Package for the Social Sciences (Version 22.0, IBM, Japan) was used for data analysis. Differences with a P-value <0.05 were considered as statistically significant, while differences with a P-value <0.10 were considered to indicate a trend towards significance.

3-3. RESULTS

3-3-1. Comparison of subjective MI vividness between MI conditions

There was no significant difference in subjective MI vividness between the dominant and non-dominant MI conditions. However, the mean VAS value of the dominant MI condition was higher than that of the non-dominant MI condition, showing a trend towards significance ($P = 0.073$, $Z = -1.793$, Figure 12).

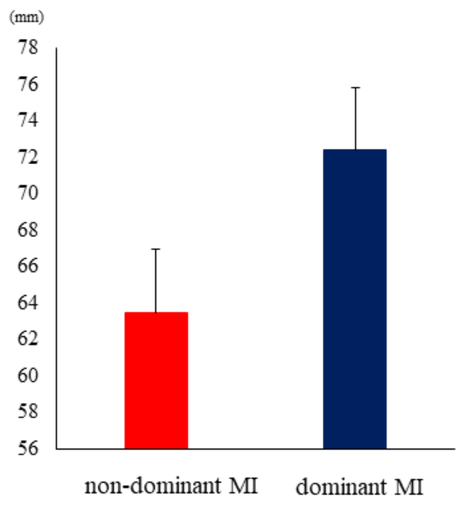

Figure 12. Comparison of VAS scores between motor imagery conditions

The VAS data were analysed using Wilcoxon's signed-rank test. The red bar indicates the mean oxy-Hb value during the non-dominant MI task, whereas the blue bar indicates the mean oxy-Hb value during the dominant MI task. The mean dominant MI value was higher than the mean non-dominant MI value, and the results showed a trend towards a statistically significant difference. MI, motor imagery; oxy-Hb, oxygenated haemoglobin; VAS, visual analogue scale.

3-3-2. Comparison of haemodynamics between MI conditions

The time course of oxy-Hb changes during MI (all participants' grand average waves) is shown in Figure 13. Two-way ANOVA for the mean oxy-Hb values revealed a significant "ROIs*condition" interaction [$F(7,13) = 2.115$, $P < 0.05$, $\eta 2 = 0.111$], whereas there was no main effect of "region of interest" [$F(7,13) = 0.753$, $P > 0.05$, $\eta 2 = 0.041$] or "condition" [$F(1,19) = 0.250$, $P > 0.05$, $\eta 2 = 0.014$]. The peak oxy-Hb time in each region of interest for the non-dominant versus dominant MI were as follows: PreSMA: 10.8 s versus 11.4 s; SMA: 11.8 s versus 12.0 s; L-PFC: 10.9 s versus 10.6 s; R-PFC: 8.6 s versus 9.9 s; L-PMA: 12.9 s versus 12.1 s; R-PMA: 11.7 s versus 10.9 s; L-SMC: 12.0 s versus 11.1 s; and R-SMC: 9.7 s versus 11.6 s. Two-way ANOVA for the peak oxy-Hb times revealed a significant main effect of "ROIs" [$F(7,13) = 2.626$, $P < 0.05$, $\eta 2 = 0.169$], whereas there was no main effect of "condition" [$F(1,19) = 0.030$, $P > 0.05$, $\eta 2 = 0.001$] or "ROIs*condition" interaction [$F(7,13) = 1.194$, $P > 0.05$, $\eta 2 = 0.049$]. Bonferroni test revealed significant differences in the peak oxy-Hb times were observed between the SMA and R-PFC ($P = 0.050$) and between the R-PFC and L-PMA ($P = 0.046$).

3-3-3. Relationship between haemodynamics and regions of interest for the MI conditions

Based on the significant "region of interest*condition" interaction, we examined the relationship between cerebral haemodynamics and ROIs during MI. The correlation results are shown in Table 1, Table 2, and Figure 14. The data were converted from raw oxy-Hb levels to oxy-Hb z-scores. A total of 25 statistically significant correlations were found for the ROIs in dominant MI data, and these were spread across both hemispheres. In contrast, only 17 statistically significant correlations were found for the ROIs in non-dominant MI data, and these were only found within the left hemisphere.

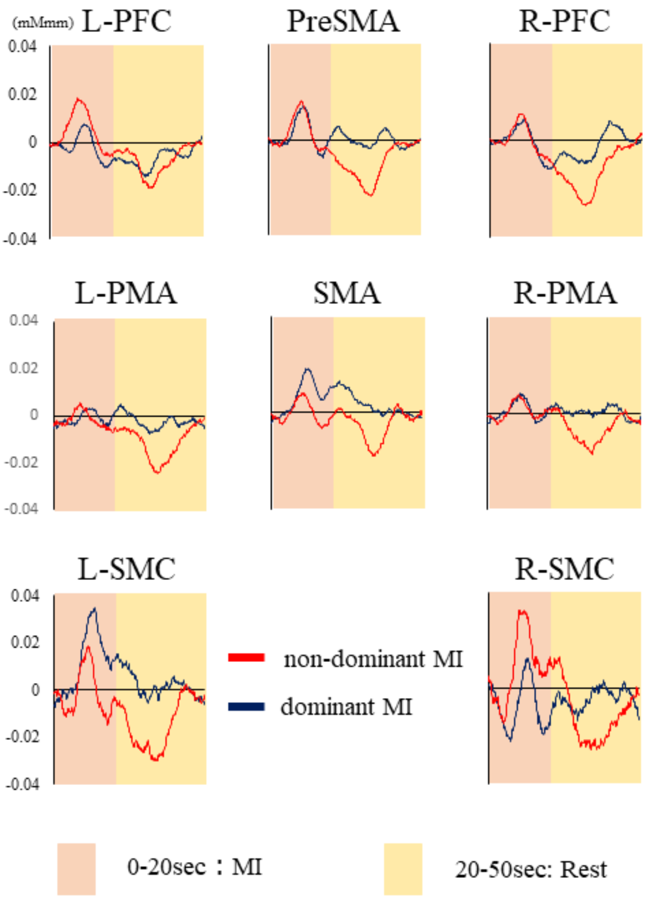

Figure 13. Time course of oxy-Hb changes

The time course of oxy-Hb changes during MI (all participants' grand average waves) is shown. The waveform was calculated by averaging the data measured over three cycles in a block design. The red line indicates oxy-Hb changes during the non-dominant MI task, and the blue line indicates oxy-Hb changes during the dominant MI task. The pink background indicates the MI task time (0–20 s), while the skin-coloured background indicates the rest time (20–50 s). MI, motor imagery; oxy-Hb, oxygenated haemoglobin.

(ρ)	PreSMA	SMA	L-PFC	R-PFC	L-PMA	R-PMA	L-SMC	R-SMC
PreSMA	1.000							
SMA	0.75*	1.000						
L-PFC	0.883*	0.574*	1.000					
R-PFC	0.792*	0.451*	0.74*	1.000				
L-PMA	0.617*	0.792*	0.402	0.326	1.000			
R-PMA	0.794*	0.771*	0.735*	0.492*	0.659*	1.000		
L-SMC	0.74*	0.534*	0.656*	0.642*	0.533*	0.561*	1.000	
R-SMC	0.719*	0.515*	0.626*	0.604*	0.451	0.56*	0.862*	1.000

Abbreviations: PFC, prefrontal cortex; PMA, pre-motor area; PreSMA, pre-supplementary motor area; SMA, supplementary motor area; SMC, sensorimotor cortex

*P < 0.05 by Spearman's rank correlation

The oxygen-haemoglobin (oxy-Hb) z-scores were analysed using Spearman's rank correlation. The shaded cells with asterisks indicate significant correlations. Twenty-five significant correlations were found.

Table 1. Haemodynamic correlations for motor imagery of the dominant hand.

(ρ)	PreSMA	SMA	L-PFC	R-PFC	L-PMA	R-PMA	L-SMC	R-SMC
PreSMA	1.000							
SMA	0.746*	1.000						
L-PFC	0.725*	0.561*	1.000					
R-PFC	0.707*	0.66*	0.537*	1.000				
L-PMA	0.721*	0.883*	0.421	0.568*	1.000			
R-PMA	0.444	0.532*	0.296	0.245	0.597*	1.000		
L-SMC	0.771*	0.621*	0.782*	0.776*	0.65*	0.297	1.000	
R-SMC	0.272	0.104	0.463	0.412	0.088	0.201	0.661*	1.000

Abbreviations: PFC, prefrontal cortex; PMA, pre-motor area; PreSMA, pre-supplementary motor area; SMA, supplementary motor area; SMC, sensorimotor cortex

*P < 0.05 by Spearman's rank correlation

The oxygen-haemoglobin (oxy-Hb) z-scores were analysed using Spearman's rank correlation. The shaded cells with asterisks indicate significant correlations. Seventeen significant correlations were found.

Table 2. Haemodynamic correlations for motor imagery of the non-dominant hand.

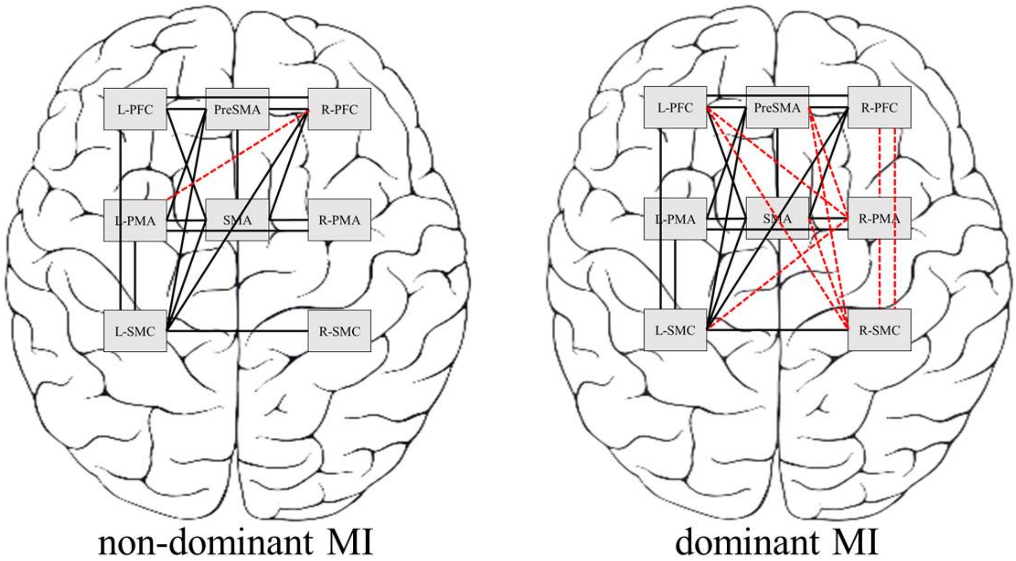

Figure 14. Haemodynamic correlations during motor imagery

The oxy-Hb z-scores were analysed using Spearman's rank correlation. The ROIs connected by black lines represent significant correlations in both conditions. The ROIs connected by red dotted lines represent significant correlations in one condition. ROIscorrelations were found in both hemispheres for the dominant MI condition but only in the left hemisphere for the non-dominant MI condition. MI, motor imagery; oxy-Hb, oxygenated haemoglobin.

3-4. DISCUSSION

In this study, we used NIRS to investigate cerebral haemodynamics during MI of self-feeding with chopsticks. Our aim was to verify if there were cerebral activation differences between dominant and non-dominant MI conditions. We found that vividness during dominant MI tended to be significantly higher than that during non-dominant MI. There was no main effect of “region of interest” or “condition,” but we found a significant “region of interest*condition” interaction for the mean oxy-Hb values. Moreover, we observed significant differences in the peak oxy-Hb times between the SMA and R-PFC, as well as between the R-PFC and L-PMA. In addition, more correlations among ROIs were found during dominant than non-dominant MI.

In the present study, we found that vividness during the dominant MI task, which involved skilful manipulation of chopsticks, had a mean value that tended to be higher than that during the non-dominant MI task, which involved non-skilful manipulation of chopsticks. A previous study using functional magnetic resonance imaging combined with TMS reported a significant activation only in the right precentral gyrus during a complex MI task performed with the left hand, as compared to performed with the right hand, although there were many overlapping activation areas between the two tasks (Kuhtz-Buschbeck et al. 2003). Another study suggested that the neural correlates for the imager’s perceived MI vividness are very specific (Lorey et al. 2011). Based on the above, MI vividness might have affected haemodynamics and may be dependent on the given MI task.

In this study, there were no significant differences in oxy-Hb mean values, indicating that oxy-Hb levels equally increase during dominant and non-dominant MI of self-feeding using chopsticks. However, peak oxy-Hb times were significantly different between the SMA and R-PFC and between the R-PFC and L-PMA, indicating that peak oxy-Hb during self-feeding MI tasks occurs significantly earlier in the R-PFC than in the SMA or L-PMA. In addition, we converted the raw haemodynamic data to z-score data, in order to examine the dynamic oxy-Hb relationships among ROIs. Haemodynamic response correlations were found both for the right and left hemispheres during dominant MI; however, such correlations were found only in the left hemisphere during non-dominant MI.

A previous study using NIRS, which investigated cerebral haemodynamics during swallowing ME and MI by comparing patients with cerebral lesions and healthy participants, showed that the peak oxy-Hb time during MI is longer in patients with cerebral lesions than in healthy adults (Kober et al. 2015). This result implies that if participants find it difficult to execute the MI, the peak oxy-Hb time is prolonged. Thus, we hypothesized that the peak oxy-Hb time during the non-dominant MI task, which is more difficult to execute, would be longer than that during the dominant MI task, which is easier to execute.

However, our results indicated no statistical differences in the peak oxy-Hb time between the two conditions. In addition, the peak oxy-Hb times were significantly different between the R-PFC and SMA and between the R-PFC and L-PMA during self-feeding MI. Nevertheless, these results are not yet sufficient to discuss the underlying mechanisms. Thus, we could not clearly conclude whether difficulty in performing MI is associated with the peak oxy-Hb time. Hence, further research is required on this topic.

Previous MI studies have reported that MI is executed dominantly by the left hemisphere (Stinear et al. 2006), and that it is more difficult to activate the right than the left hemisphere using MI tasks (Wang et al. 2014). Moreover, in a study that compared brain connectivity, stronger connectivity was observed in the left hemisphere, including the SMC, PMA, and SMA during a dominant MI task in healthy adults, while stronger connectivity was observed in the right hemisphere during the same task in patients with right hemiplegia (Wang et al. 2016). Therefore, cortical activation occurs primarily in the left hemisphere during MI tasks; however, the left and right hemispheres are connected to each other, and it is possible that the connectivity strength is reflected by MI vividness. Hence, it is possible that haemodynamic correlations are affected by MI vividness, as more correlations among ROIs were found during dominant MI. This means that, in the case of the self-feeding activity with chopsticks, it was more difficult for participants to perform MI vividly during the non-dominant MI condition (i.e., manipulate the chopsticks with the left hand), which is representative of movement non-proficiency, than during the dominant MI condition (i.e., manipulate the chopsticks with the right hand), which is representative of movement proficiency. That may explain why the haemodynamic response correlations among ROIs were limited in the non-dominant MI condition.

3-4-1. Research limitations

In this study, the participants were all right-handed healthy adults who were skillful at chopsticks manipulation; thus, it is unclear whether our results are generalizable to left-handed individuals and those with disease, disability, or who are not skillful with chopsticks. Second, no participants reported a very low rate of MI vividness; therefore, it remains unclear whether haemodynamic differences would be observed between participants with high and low MI vividness. Finally, the sample size of our study was small. Based on these limitations, future studies should include patients with various conditions who might benefit from MP of various tasks, including left-handed subjects. In addition, cerebral activation during MI of other ADLs should be assessed.

3-4-2. Conclusion

The haemodynamic response correlations were spread across both hemispheres during MI with the dominant hand but were restricted to the left hemisphere during MI with the non-dominant hand. These differences suggest that MI vividness differences are caused by movement proficiency differences, which may affect haemodynamic responses. The present study provides further insight regarding MI, as well as new ideas about the use of MI for rehabilitation of ADLs. Thus, our results may contribute to the development of a standardized methodology for MP using MI in rehabilitation.

CHAPTER 4
GENERAL DISCUSSION AND CONCLUSION

With advances in neuroimaging systems, many researchers have tried to investigated cortical activation during MI tasks using the system such as NIRS, magnetic resonance imaging and TMS and suggested that MI relies on a network involving motor-related regions, including the PMA, SMA, parietal lobule, cerebellum, and basal ganglion, which supports the view that ME and MI are very similar processes (for meta-analysis see Hetu et al., 2013). Previous studies have investigated cerebral activation during MI of simple tasks (Wriessnegger et al. 2008; Roosink et al. 2010; Feurra et al. 2011). However, most of these reports used simple movements as tasks; only a few reports, to date, have used complex movements that are essential in clinical scenarios in rehabilitation medicine.

In Chapter 2, We investigated the cerebral hemodynamics associated with the MI and ME of a self-feeding activity with chopsticks using NIRS. I recorded oxy-Hb changes of the motor-related cerebral areas (Pre-SMA, SMA, bilateral PFC, bilateral PMA, and bilateral SMC). The oxy-Hb during ME were significantly higher in the L-SMC than in the SMA and the L-PMA, whereas there were no apparent differences between ROIs during the MI. Furthermore, significantly higher oxy-Hb levels were detected in the SMA and the L-PMA during MI, in contrast to the levels that were observed during the ME. In the field of rehabilitation, further aim of MP is to improve actual performance of ADLs among patients. Therefore, in order to standardize MP methodology using complex MI tasks such as self-feeding with chopsticks, my study should reflect handedness.

For the reason, in Chapter 3, we investigated differences in cerebral hemodynamics during MI of self-feeding with chopsticks using the dominant or non-dominant hand with NIRS. The vividness during dominant MI tended to be significantly higher than that during non-dominant MI. Then, there were significant differences in the peak oxy-Hb times between the SMA and R-PFC, as well as between the R-PFC and L-PMA. In addition, more correlations among ROIs were found during dominant than non-dominant MI.

According to these results, we suggest that the task was easy for them and they could carry it out expertly and did not need to intentionally implement the cognitive process because the SMA and PMA are known to play roles in motor planning, motor preparation, and motor learning (Hoshi et al., 2004; Nakayama et al., 2008; Wang et al., 2016). Thus, the SMA and PMA activation might have been reduced during ME, and the differences in the SMA and PMA activation between ME and MI might be related to a need for intentional cognitive processes. Moreover, cerebral activity can differ according to MI vividness (Williams et al. 2012). Also, MI with dominant-hand increased more cerebral activation than MI with non-dominant-hand (Kuhtz-Buschbeck et al. 2003). Therefore, haemodynamic correlations were affected by MI vividness, as more correlations among ROIs were found during dominant MI. Hence, levels of activation in the SMA and PMA during ME and MI were affected by the necessity of intentional cognitive processes, and the levels of activation can be changed by levels of the movement proficiency.

The clinical implications of the current findings can be summarized as follows: It is likely that MP with complex MI tasks relating ADLs can be useful for rehabilitation in a clinical setting. To apply MP in clinical scenarios, patients imagine given actions repetitively despite performing actual movements. Typically, these given actions were simple tasks which compose complex actions such as ADLs. According to the present results, the use of complex tasks directly for MI has possibilities further enhance the clinical efficacy of MP. Thus, our findings expand the knowledge base of MI, and provides further understanding of the use of MI in rehabilitation for ADLs. Therefore, this study might contribute to the application of MP in clinical situations.

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