

Research Article

A method for using video presentation to increase the vividness and activity of cortical regions during motor imagery tasks

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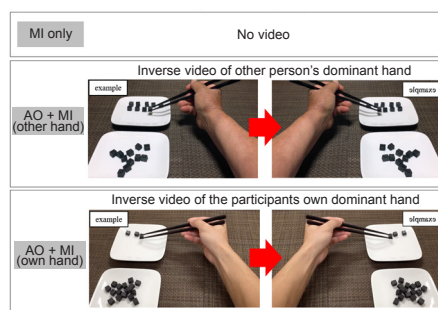
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Graphical Abstract Changes in motor imagery (MI) vividness and hemodynamic changes in the cerebral cortex during MI performance under the following three conditions in near-infrared spectroscopy



Abstract

In recent years, mental practice (MP) using laterally inverted video of a subject's non-paralyzed upper limb to improve the vividness of presented motor imagery (MI) has been shown to be effective for improving the function of a paralyzed upper limb. However, no studies have yet assessed the activity of cortical regions engaged during MI task performance using inverse video presentations and neurophysiological indicators. This study sought to investigate changes in MI vividness and hemodynamic changes in the cerebral cortex during MI performance under the following three conditions in near-infrared spectroscopy: MI-only without inverse video presentation (MI-only), MI with action observation (AO) of an inverse video presentation of another person's hand (AO + MI (other hand)), and MI with AO of an inverse video presentation of a participant's own hand (AO + MI (own hand)). Participants included 66 healthy right-handed adults (41 men and 25 women; mean age: 26.3 ± 4.3 years). There were 23 patients in the MI-only group (mean age: 26.4 ± 4.1 years), 20 in the AO + MI (other hand) group (mean age: 25.9 ± 5.0 years), and 23 in the AO + MI (own hand) group (mean age: 26.9 ± 4.1 years). The MI task involved transferring 1 cm \times 1 cm blocks from one plate to another, once per second, using chopsticks held in the non-dominant hand. Based on a visual analog scale (VAS), MI vividness was significantly higher in the AO + MI (own hand) group than in the MI-only group and the AO + MI (other hand) group. A main effect of condition was revealed in terms of MI vividness, as well as regions of interest (ROIs) in certain brain areas associated with motor processing. The data suggest that inverse video presentation of a person's own hand enhances the MI vividness and increases the activity of motor-related cortical areas during MI. This study was approved by the Institutional Ethics Committee of Nagasaki University Graduate School of Biomedical and Health Sciences (approval No. 18121303) on January 18, 2019.

Key Words: action observation; cortical activity; inverse video presentation; mental practice; motor imagery; motor palsy; paralysis; recovery; rehabilitation; stroke

Chinese Library Classification No. R493; R364; R741

Introduction

Several methods have been employed to improve rehabilitation of paralyzed upper limbs post-stroke, including motor therapy, functional electrical stimulation, repeated mental practice (MP) with motor imagery (MI), action observation (AO), and brain machine interfaces (BCIs) (Sharma et al., 2006; Ruffino et al., 2017; Lin and Dionne, 2018;

Buchignani et al., 2019; Coscia et al., 2019). MP is a safe, cost-effective strategy, with unlimited opportunities for practice (Kho et al., 2014). Most studies have shown that MP reduces impairments and improves functional upper limb recovery post-stroke (Nilsen et al., 2010), although those with motor paralysis had significantly lower MI vividness than healthy subjects (de Vries et al., 2011), and MP may not enhance motor recovery in the early period post-stroke (Ietswaart et

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al., 2011). A meta-analysis demonstrated promising benefits of MP in post-stroke rehabilitation; however, the optimal amount of MP, the method of video presentation, and the effects of visual and kinesthetic MI, and imagery perspective have not been elucidated (Nilsen et al., 2010).

Therefore, research to improve vividness of MI during video presentation has attracted attention. Independent use of MI and AO has been largely effective, and there is evidence that the two processes can elicit similar motor system activity changes (Eaves et al., 2016). Recent neuroimaging studies demonstrated enhanced cortical activity and improved performance when AO and MI were performed concurrently ("AO + MI"), compared to either AO or MI being performed alone (Vogt et al., 2013; Taube et al., 2015). Others have assessed differences in visual perspectives used in AO, showing that the first-person perspective is more effective than the third-person perspective in inducing brain activity in motor processing areas (Ruby and Decety, 2001, 2003). AO of a subject's own hand induces greater primary motor area (PMA) activity than video presentation of another person's hand (Maeda et al., 2001). Clinically, however, some patients are unable to move paralyzed upper limbs, making it impossible to film their actions. Mirror therapy (MT) produces muscular movement sensations in the paralyzed upper limb by reflecting the movement of the non-paralyzed counterpart using a mirror box (Altschuler et al., 1999), providing patients with a "proper" visual input and giving the illusion that the affected arm is moving unimpaired. A meta-analysis indicated that combining MT with another rehabilitation method to improve upper extremity motor function post-stroke is better than relying solely on monotherapies (Luo et al., 2020). In recent years, MP using laterally inverted video presentation of a subject's non-paralyzed upper limb to improve MI vividness has been effective in improving paralyzed upper limb function (Iso et al., 2016b); this effect was maintained after therapy ended. Although MP with inverse video presentation was effective in a single case intervention study, none have been conducted on a large number of subjects or assessed cortical activity during MI processing using neurophysiological indicators, such as near-infrared spectroscopy (NIRS).

This study aimed to investigate changes in MI vividness and hemodynamic changes in the cerebral cortex during MI performance under the following three conditions in near-infrared spectroscopy: MI-only (without inverse video presentation), MI with inverse video presentation of another person's hand, and MI with inverse video presentation of a participant's own hand.

Participants and Methods

Participants

Participants were right-handed, healthy adults with no history of neurological disease, respiratory disease, stroke, or dementia, who had provided informed consent prior to enrollment.

This study was approved by the Institutional Ethics Committee of Nagasaki University Graduate School of Biomedical and Health Sciences (approval No. 18121303) on January 18, 2019. Recruitment was conducted from February 2019 to February 2020, and participants were informed about the study and signed a consent form before participating in the study. All study procedures were conducted in accordance with the *Declaration of Helsinki* (World Medical Association, 2013).

Participants were administered the Edinburgh Handedness Inventory (el Maniani et al., 2016). All were right-handed. The total sample size required was determined statistically using G* Power software (Erdfelder et al., 1996); a two-way analysis of variance (ANOVA) yielded a power of 0.8 for a probability of error of 0.05 and an effect size of 0.4, giving a total sample

size requirement of 64 participants.

Participants were randomly assigned to one of the following three groups using the software's Excel function RAND: a group that was not presented with a laterally inverted video during the MI task (MI-only), a group that was presented with an inverse video of another person's hand (AO + MI (other hand)), and a group that was presented with an inverse video of the participant's own hand (AO + MI (own hand)). It has been reported that cerebral hemodynamics decrease during visualization of MI when subjects are fatigued or sleep deprived (Suda et al., 2009). Participants were only allowed to participate in the experiment after confirming that they did not feel sleep deprived or fatigued.

The participants consisted of a total of 66 healthy, right-handed adults (41 men and 25 women; mean age: 26.3 ± 4.3 years). There were 23 participants in the MI-only group (mean age: 26.4 ± 4.1 years), 20 in the AO + MI (other hand) group (mean age: 25.9 ± 5.0 years), and 23 in the AO + MI (own hand) group (mean age: 26.9 ± 4.1 years).

Study design

The MI task involved transferring 1 cm × 1 cm blocks from one plate to another every second using chopsticks held in the non-dominant hand. The experimental protocol is shown in **Figure 1**. Before the MI task, the participants were asked to practice transferring twenty 1 cm × 1 cm blocks between plates based on the rhythm of a metronome (1 Hz; i.e., one block per second) (Avanzino et al., 2015) using chopsticks held in the dominant hand. As soon as each participant was able to accomplish this, the MI task was performed to assess MI vividness with chopsticks held in the dominant hand. The subjective MI vividness was assessed using a Visual Analogue Scale (VAS) (Malouin et al., 2008; Mizuguchi et al., 2019). This is a subjective assessment of how well the MI was performed with the non-dominant hand, using chopsticks to carry the block, and how vivid the MI was. Briefly, participants were asked to mark a location on a 100 mm horizontal line according to the vividness of the MI they experienced, the two ends of which were labeled "0 = no MI at all," and "100 = very vivid MI."

In order to create a video to be presented during the MI task, we used a smartphone (iPhone XS, Apple, Cupertino, CA, USA) to film an individual moving blocks from plate-to-plate using chopsticks held in the dominant hand. The video was edited with a free application (SymPlayer, Masiyo Tachikawa, Japan; iMovie, Apple) to create a presentation video of a non-dominant hand moving a block from plate-to-plate with chopsticks once per second (**Figure 2**). Two inverse videos were created: one showing a block being moved using chopsticks held in a participant's own hand and the other with the chopsticks held in another person's hand. For the latter, videos of the dominant hands of a man and a woman in their 60s were filmed. This was done purposefully so that the hands were clearly different in age and of the opposite sex compared with the participants' own hands.

In the experiment, the performances of the three randomly assigned groups were compared. The use of chopsticks held in the non-dominant hand was conducted once without practice to evaluate performance, and the MI vividness was assessed with chopsticks held in the non-dominant hand. In this MI task, participants were instructed to perform the task using kinesthetic MI (Jackson et al., 2006), as if they were actually performing the movement, but without contracting the muscles. The participants were instructed to maintain the same position and to try to relax without thinking during the resting period. Immediately after the near-infrared spectroscopy (NIRS) measurements were completed, we assessed the subjective vividness of MI. During the measurement, the MI-only group was instructed to look at

the block on the plate with their eyes open, while the AO + MI (other hand) and AO + MI (own hand) groups were instructed to watch the video. The study is open-label, and no blinding was performed.

NIRS measurements and analyses

The NIRS measurements were conducted using an optical topography system (ETG4000, Hitachi Medical Corp., Tokyo, Japan). Participants were assessed in a quiet, private evaluation room (room temperature: 24°C) at Nagasaki Rehabilitation Hospital. The measurements were conducted with the participant seated in a chair with both upper limbs on the table; the table had chopsticks and a plate with a block in front of it. The participants were seated with their hips pressed to the back of the chair, their spines against the backrest, the soles of their feet in contact with the floor, and both upper limbs placed with the forearm and palm facing down on the table.

The NIRS probes were placed in a 4 × 4 optode probe configuration with respect to Cz, according to the international 10–20 method (eight incident lights and eight detector fibers), resulting in a total of 24 channels, with an inter-optode distance of 3.0 cm (Okamoto et al., 2004), as shown in **Figure 3**. The continuous wave NIRS system emitted at two different wavelengths (625 and 830 nm) over the scalp, and the relative change in absorption of the near-infrared light were measured. These values are based on the modified Beer-Lambert (Cope and Delpy, 1998; Obrig and Villringer, 2003; Baker et al., 2014), oxygenated hemoglobin (Oxy-Hb), and deoxygenated hemoglobin (Deoxy-Hb) concentrations. It has been reported that there is no difference in the optical path length of the left and right target region for this NIRS probe (Cope and Delpy, 1998). NIRS measurements have been reported to be non-invasive, safe, and reproducible (Ito et al., 2000; Kakimoto et al., 2009).

The regions of interest (ROIs) were the sensorimotor cortex (SMC), the pre-motor area (PMA), the prefrontal cortex (PFC), the pre-supplementary motor area (pre-SMA), and the supplementary motor area (SMA) (**Figure 3**). Based on our previous studies, we have identified channels 18 and 22 as recording above the left SMC, channels 21 and 24 recording above the right SMC, channels 9, 12, 13, and 16 above the SMA, and channels 2, 5, and 6 above the pre-SMA (Hatakenaka et al., 2007; Amemiya et al., 2010; Sagari et al., 2015; Iso et al., 2016a). Channels 8, 11, and 15 were above the left-PMC, channels 10, 14, and 17 channels were above the right-PMA. Channels 1 and 4 were above the left-PFC, channels 3 and 7 were above the right PFC. Channels 19, 20, and 23 were not further analyzed (Hatakenaka et al., 2007; Amemiya et al., 2010; Sagari et al., 2015; Iso et al., 2016a). For the SMC, studies using NIRS experiments have treated the sensory area and motor cortex as a whole (Hatakenaka et al., 2007; Amemiya et al., 2010; Sagari et al., 2015). The NIRS measurements were based on a block design, with three consecutive cycles of alternating 20 second MI tasks and 30 second resting periods for each condition (Iso et al., 2016a). Since it has been reported in a previous NIRS signal study of the rat brain that Oxy-Hb concentration is an indicator of changes in regional cerebral blood volume and a more sensitive parameter for measuring brain activation than Deoxy-Hb (Hoshi et al., 2001), we adopted the change in Oxy-Hb concentration occurring during the MI task as an indicator of regional changes in cerebral hemodynamics. Both NIRS and functional magnetic resonance imaging (fMRI) studies exhibited similar changes in cerebral hemodynamics during the task, and the results are not affected by blood flow of the skin (Sato et al., 2013). The data were analyzed for changes in Oxy-Hb concentrations in each region in an integral mode, which averages three cycles of data. For the baseline measurement, the average of the 5 second period

immediately before and after the end of the task was used (Marumo et al., 2009; Pu et al., 2012). Considering the time until cerebral blood flow increased in accordance with neural activity, the usable performance data were collected from 5 seconds after the start of the task to 20 seconds after the end of the task (Bakalova et al., 2001; **Figure 4**).

The measured data were filtered using a 3 Hz high-pass filter, which was 0.1 standard deviation above the wave analysis, as previously reported (Iso, 2016; Matsuo et al., 2019). This filter was used to exclude noise such as hyperactivity due to skin and blood dynamics, marking the channels with higher noise levels (Takahashi et al., 2011). When obvious artifacts were found, they were removed from the waveform. The average waveform was calculated by integral analysis. In addition, the Oxy-Hb values in each of the regions were converted to Z-scores for comparisons.

Statistical analysis

Statistical Package for the Social Sciences software (SPSS version 22.0, IBM, Armonk, NY, USA) was used for statistical analysis. One-way analysis of variance (ANOVA) was conducted to compare the number of blocks transferred between dishes using chopsticks with the non-dominant hand and VAS scores among the three video presentation groups outlined above. A two-way ANOVA was conducted to compare Z-scores of the ROI measurements in the brain regions (PFC, PMA, pre-SMA, SMA, and SMC) and the three video presentation conditions. Bonferroni *post hoc* test was used in all cases when warranted by the results of the ANOVAs. All levels of significance were set at $P < 0.05$.

Results

Comparison of MI performance using non-dominant hands

In the MI task, we evaluated the number of times participants were able to transfer one block per second using chopsticks with the non-dominant hand as a real action. The MI-only group had a mean number of transfers of 9.3 (± 1.0), the AO + MI (other hand) had a mean of 11.05 (± 1.3), and the AO + MI (own hand) had a mean of 9.6 (± 1.2), with no significant difference between the groups (**Figure 5**).

MI vividness

MI vividness was assessed using a VAS after performing NIRS measurements. A main effect of condition was observed; the MI-only group had a mean score of 48.8 mm (± 4.9), the AO + MI (other hand) had a mean score of 45.2 mm (± 6.0), and the AO + MI (own hand) group had a mean score of 74.4 mm (± 5.0). Furthermore, the *post hoc* test showed that MI vividness was significantly lower in the MI-only and AO + MI (other hand) groups compared to the AO + MI (own hand) group ($P < 0.01$; **Figure 6**).

Activity of cortical areas during performance of the MI task

Over the time course of the MI task, each ROI we assessed was activated in all three conditions: MI-only, AO + MI (other hand) and AO + MI (own hand) groups (**Figure 7**). In the MI task, we compared the Z-scores of the ROIs across the three conditions to identify the best way to improve the vividness of MI and the activation of cortical regions engaged by MI task performance. The results showed a main effect of condition on ROIs measured in the assessed brain regions, but no interaction was observed. For this reason, comparisons between conditions and ROIs were conducted in follow-up *post hoc* comparisons. The values were significantly higher in the AO + MI (own hand) group than in the MI-only and AO + MI (other hand) groups (**Figure 8**). Significant differences were found between ROIs, in particular the right PFC, right SMC, and SMA (**Figure 9**).

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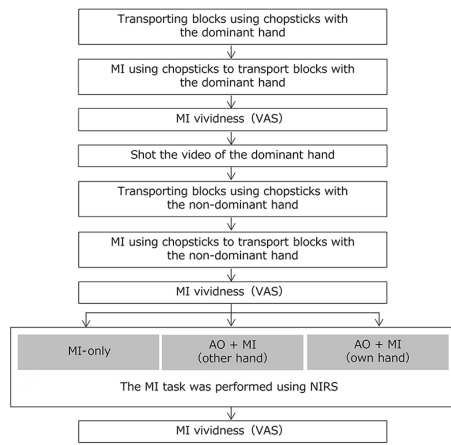


Figure 1 | Experimental protocol.

The experimental protocol consisted of three conditions: MI-only, or MI with AO, with presentation of a video depicting the participant's own hand (AO + MI (own hand)) or another person's (AO + MI (other hand)). AO: Action observation; MI: motor imagery; NIRS: near-infrared spectroscopy; VAS: visual analog scale.

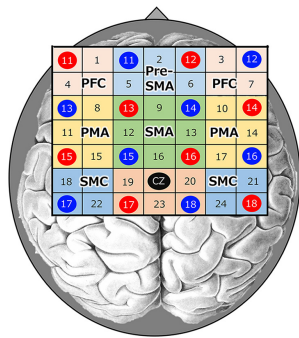


Figure 3 | Diagram showing the channel configuration of the 4 × 4 optode probe set.

The NIRS probes were arranged with reference to Cz according to the international 10–20 method. The red and blue circles indicate the locations of the NIRS sensors and detectors, respectively. The regions of interest were the SMC, PMA, PFC, pre-SMA, and SMA. Based on our previous studies, channels 18 and 22 were above the left SMC, and channels 21 and 24 were above the right SMC. Channels 9, 12, 13, and 16 were above the SMA, and channels 2, 5, and 6 were above the pre-SMA. Channels 8, 11, and 15 channels were above the left-PMA, and channels 10, 14, and 17 were above the right-PMA. Channels 1 and 4 were above the left-PFC, and channels 3 and 7 channels were above the right PFC. Channels 19, 20, and 23 were not further analyzed. NIRS: Near-infrared spectroscopy; PFC: prefrontal cortex; PMA: pre-motor area; pre-SMA: pre-supplementary motor area; SMA: supplementary motor area; SMC: supplementary motor cortex.

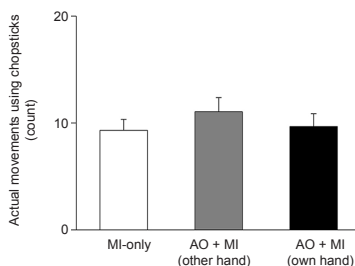


Figure 5 | The average number of actual movements performed to transfer blocks from one plate to another once per second using chopsticks held in the non-dominant hand for each condition.

The white bar shows data for the performance of the MI task without AO. The gray and black bars show data for MI performance with AO, with a video presentation of another person's hand and the participant's own hand, respectively. A one-way analysis of variance was performed for the number of blocks transferred from plate-to-plate using chopsticks with the non-dominant hand in the MI-only group (23 participants), AO + MI (other hand) group (20 participants), and AO + MI (own hand) group (23 participants). Data are expressed as the mean ± SE. AO: Action observation; MI: motor imagery.

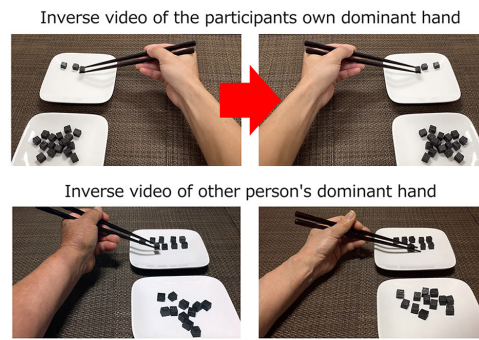


Figure 2 | Examples of laterally inverted video presented to a participant of either his or her own dominant hand or another person's.

The video was recorded with a smartphone, and then the video was inverted with free application software. Therefore, the inverse video showed a depiction of chopsticks being held in a participant's non-dominant hand as small blocks were transferred from one plate to another at a rate of one per second. For the condition where the videos depicted another person's hand, the dominant hands of a man and a woman in their 60s were filmed to assess differences in task performance between conditions.

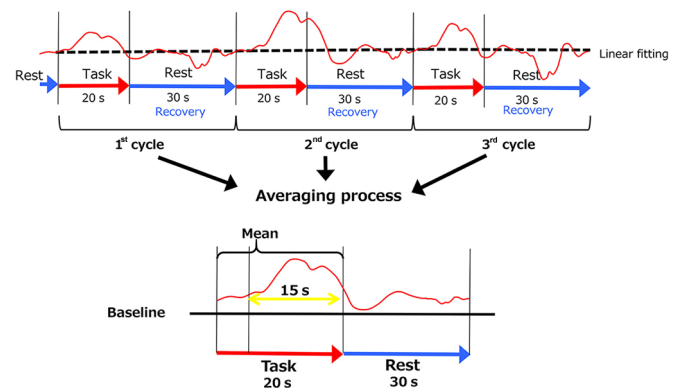


Figure 4 | Analysis of NIRS waveforms using the integral method.

The red curve represents one case of a false NIRS waveform. The average waveforms were created by determining the mean of data measured in a three-cycle block design. The vertical axis shows Oxy-Hb concentration (mM•mm) and the horizontal axis shows the time course of one cycle of task performance and rest periods. The average value of Oxy-Hb measured between 5 and 20 seconds during the task (15 seconds, yellow line in the averaged graph) was calculated. NIRS: Near-infrared spectroscopy; Oxy-Hb: oxygenated hemoglobin.

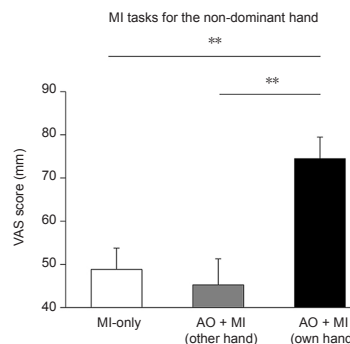


Figure 6 | Vividness of MI evaluated for each condition (without AO or with AO with a video depicting the participant's own hand or another person's) using a VAS.

The vertical axis represents the value of MI vividness, where "0 = No MI at all," and "100 = very vivid MI." 23, 20, and 23 participants in the MI-only, AO + MI (other hand), and AO + MI (own hand) group, respectively. Data are expressed as the mean ± SE. ***P* < 0.01 (one-way analysis of variance followed by Bonferroni *post hoc* test). AO: Action observation; MI: motor imagery; VAS: visual analog scale.

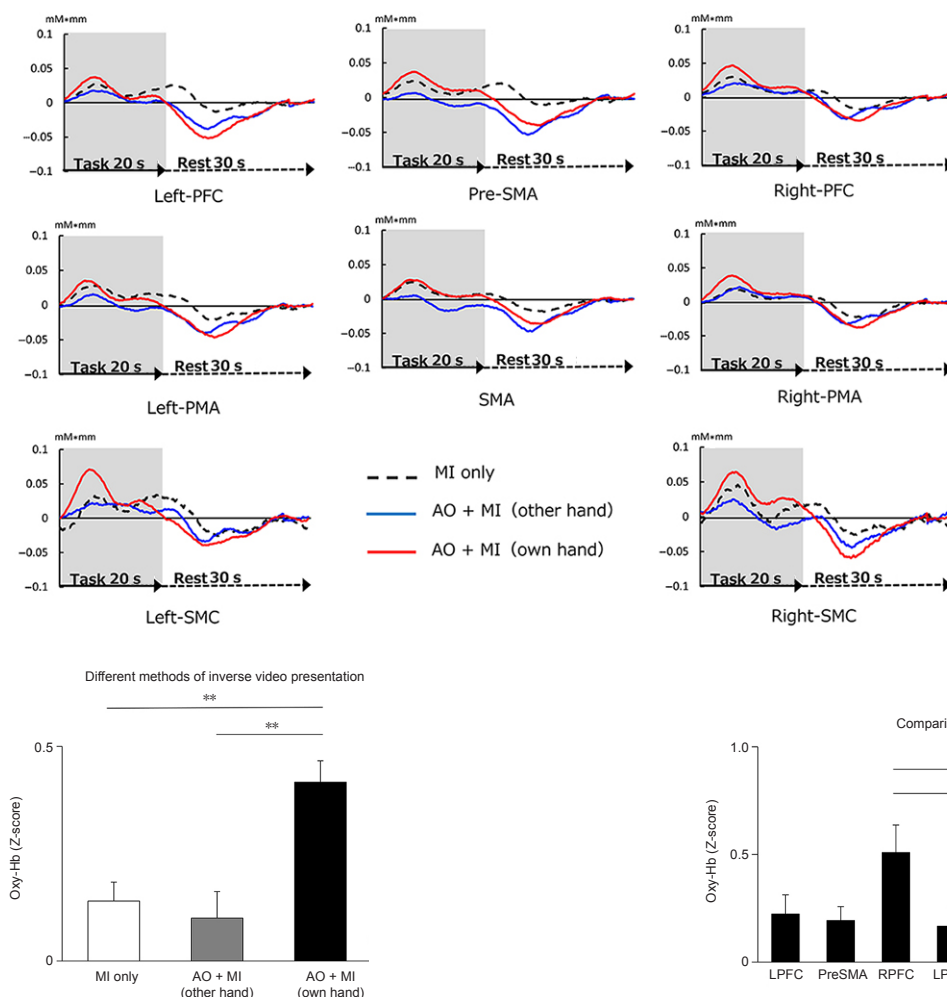


Figure 8 | Z-score of all regions of interests (PFC, PMA, Pre-SMA, SMA, and SMC) during MI of the upper extremity in the MI-only group (23 participants), AO + MI (other hand) group (20 participants), and AO + MI (own hand) group (23 participants).

The vertical axis indicates the value of Oxy-Hb in MI. With respect to the comparison between conditions, the value in the AO + MI (own hand) group was significantly higher than that in the MI-only group and AO + MI (other hand) group (two-way analysis of variance followed by Bonferroni *post hoc* test). Data are expressed as the mean \pm SE. ** $P < 0.01$. AO: Action observation; MI: motor imagery; Oxy-Hb: oxygenated hemoglobin; PFC: prefrontal cortex; PMA: primary motor area; pre-SMA: pre-supplementary motor; SMA: supplementary motor area; SMC: sensorimotor cortex.

Discussion

In this study, we investigated changes in the cerebral hemodynamics of cortical regions, as well as vividness during MI task performance.

MI vividness

As a means to increase the vividness of MI, research into combining MI and AO has attracted attention, and studies on video presentation have been performed. Such studies using video presentations have shown differences based on the perspective used in AO; a first-person perspective was more effective than a third-person perspective in inducing activity in the somatosensory cortex of the brain (Ruby et al., 2003). Furthermore, studies have also shown that video presentation of another person's hand induces lesser changes in brain activity in the PMA than when a person's own hand is presented (Maeda et al., 2001). In a study of the effect of hand angle in the presented image, a medial-lateral effect was observed in that the responses were faster for images where the third finger was rotated toward the midline of the body

Figure 7 | Time course of changes in Oxy-Hb concentration in various brain regions during MI task performance.

The vertical axes show the changes in Oxy-Hb concentration and the horizontal axes shows the time courses. The solid red line indicates the group performing the MI with AO with a video presentation of the participant's own hand (AO + MI (own hand)), the solid blue line indicates the group performing the MI task with AO with a video presentation of another person's hand (AO + MI (other hand)), and the dotted line indicates the group performing the MI alone without AO. The gray shaded area indicates the time over which the task was performed. The time courses were averaged across all participants. 23, 20, and 23 participants in the MI-only, AO + MI (other hand), and AO + MI (own hand) group, respectively. AO: Action observation; MI: motor imagery; Oxy-Hb: oxygenated hemoglobin; PFC: prefrontal cortex; PMA: pre-motor area; SMC: supplementary motor area.

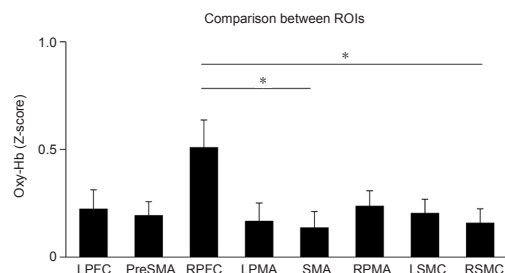


Figure 9 | Oxy-Hb values in the MI task in 66 subjects were calculated by Z-score for each ROI, and mean values of Z-score for each ROI.

Quantification of Oxy-Hb concentrations by regions of interest in certain brain areas. The vertical axis indicates the Oxy-Hb concentrations during upper limb MI task performance. Significant differences were found between the RPF and RSMC and SMA. 23, 20, and 23 participants in the MI-only, AO + MI (other hand), and AO + MI (own hand) group, respectively. Data are expressed as the mean \pm SE. * $P < 0.05$ (one-way analysis of variance followed by Bonferroni *post hoc* test). LPFC: Left prefrontal cortex; LPMA: left primary motor area; LSMC: left sensorimotor cortex; MI: motor imagery; Oxy-Hb: oxygenated hemoglobin; PreSMA: pre-supplementary motor area; ROI: region of interest; RPF: right prefrontal cortex; RPMA: right pre-motor area; RSMC: right sensorimotor cortex; SMA: supplementary motor area.

than in images where it was rotated in the opposite direction, and we inferred that an MI strategy was primarily employed (ter Horst et al., 2010; Nagashima et al., 2019). To summarize what has been reported in previous studies, the video presentation should ideally be shown from the first-person perspective (kinesthetic MI) and should be of a subject's own hand, not another person's hand. In addition, the hand in the biomechanically constrained position is considered to be more susceptible to MI. In this MI task, we filmed the images of hands of others and the participants' own hands from the first-person, subjective perspective from the angle in which the hands would be used in daily life. Therefore, we believe that MI vividness was significantly higher in the AO + MI (own hand) group.

Activation of cortical regions in different video presentation conditions

The greatest change in Oxy-Hb values was found in cortical regions for all three presentation conditions. Post hoc results showed that Oxy-Hb concentrations in cortical areas were significantly higher in the AO + MI (own hand) group than in

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the MI-only and AO + MI (other hand) groups. As mentioned above, brain activity in the PMC was greater when AO was performed using the video of a participant's own hand than that of another person's hand (Maeda et al., 2001). Furthermore, in a study assessing concomitant AO + MI task performance, dart throwing, basketball tossing, and golfing tasks were performed under the AO-only, MI-only, and AO + MI conditions, with the results showing that the performance of the AO + MI group was better than that of AO alone or MI alone in all assessed tasks (Wright et al., 2018; Smith et al., 2019; McNeill et al., 2020a, b). From these studies, it could be concluded that the conditions for better performance were the use of the participant's own hand video and the combined use of AO + MI. Therefore, it can be presumed that the cortical area was activated under the condition of own hand AO + MI in the present experiment.

Activity in cortical areas during the MI tasks

In a study using NIRS to compare the activity of cortical regions based on changes in concentration of hemoglobin during the finger tapping tasks with motor execution (ME) and kinesthetic MI, greater activation was observed for the ME condition in the motor cortex, including in the PMA, SMA, PMC, and SMC. Also, in the MI condition, more activation was observed in the motor cortex, including the SMC, which is consistent with previous observations in studies using fMRI (Batula et al., 2017; Wu et al., 2018). Therefore, we believe that the SMA and right SMC were active in the MI task in this experiment.

In an NIRS study using smartphone flick input tasks, the left SMC, SMA, and right PFC exhibited significant changes in cerebral blood flow dynamics as the task cycles progressed, indicating motor learning over time. These changes in activity likely reflect distinct aspects of acquisition of the motor task, such as increased finger momentum, motor inhibition, and visual working memory in the left SMC, SMA, and right PFC, respectively (Sagari et al., 2015). Therefore, the fact that the activity of the right PFC region was higher than that of the right SMC and SMA in the present experiment may be due to the fact that it was at an early stage of learning the MI task. This NIRS study provided us with further information on the activity of cortical regions during MI in different video presentations. In contrast, the functional MRI studies allow us to analyze a wide range of areas active during MI, except for the cerebral cortex. Thus, our study could reveal basic knowledge to inform research using MRI for developing MP methodologies in the future.

Clinical application of MI using inverse video presentation

These results may provide a means of improving the vividness of MI during rehabilitation in stroke patients, which has been a problematic issue with MP performance, as described in previous studies. It has been reported that MP can be applied to each stage of stroke rehabilitation, permitting patients to begin training earlier, even in states of flaccid paralysis (Zimmermann-Schlatter et al., 2008; Tong et al., 2017). This indicates that MP can be performed in clinical settings, regardless of the severity of motor palsy affecting the upper limb.

Most studies have shown that MP reduces impairments and improves functional upper limb recovery post-stroke. However, it has been noted that further research is needed on the effects of appropriate amounts, methods of video presentation, and video perspectives (Nilsen et al., 2010). In this study, we were able to solve the problem of the video presentation method and the viewpoint of the images. Also, although the MI task used in this study was performed on the upper extremities, there are reports of improved performance in the lower extremities, as well, with combined AO + MI treatment (Villiger et al., 2013). With regard to the future

prospects of the use of NIRS, a systematic review showed that NIRS is a viable tool to detect functional differences between patients with chronic neurological diseases and older adults (Bonilauri et al., 2020). Therefore, we consider NIRS to be one of the effective methods to objectively evaluate brain activity. Along with the present results, this supports the utility of inverse video presentation when performing MP with AO + MI in patients with stroke with motor palsy of the upper or lower limbs. We can also use NIRS to measure brain activity in cortical regions of AO + MI using an inverted video of the non-paralyzed upper and lower limbs, which can be communicated using objective data.

Limitations

In the present study, healthy adults performed an MI task using chopsticks held with the non-dominant hand. However, not all tasks that are difficult to perform in the non-dominant hand result in the same changes in cortical area activity. In the present MI task, there was no interaction between the MI-only, the AO + MI (other hand), and the AO + MI (own hand) conditions and ROIs. From this, it was not clear which regions were more active under the AO + MI (own hand) condition. In this study, the only neurophysiological indicator used to analyze the activity of cortical regions, mainly motor-related areas, is NIRS. Thus, the activity in other cortical areas is not yet well known; in addition, it remains unclear whether other neurophysiological indicators such as MRI scans may show similar results as those which were observed in this study.

Conclusions

The group that was presented with the video of the participant's own hand exhibited significantly higher values for MI vividness and significantly greater activation in cortical areas than the MI-only group and the group that was presented with video of another person's hand. In this study, we presented an inverse video of the participant's own hand in an MI task that is difficult to perform with the non-dominant hand. Performing AO + MI with video of a subject's own hand can increase the vividness of MI and activate motor areas during the MI task to improve post-stroke rehabilitation. Thus, to improve rehabilitation after stroke, AO + MI using the subject's own hand images may improve the clarity of MI and activate the motor cortex during the MI task, and furthermore, practicing this may improve performance.

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Declaration of participant consent: The authors certify that they have obtained all appropriate participant consent forms. In the forms the participants have given their consent for their images and other clinical information to be reported in the journal. The participants understand that their names and initials will not be published and due efforts will be made to conceal their identity.

Reporting statement: This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement.

Biostatistics statement: The statistical methods of this study were reviewed by the biostatistician of Nagasaki University in Japan.

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