Action Observation of Own Hand Movement Enhances Event-Related Desynchronization

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***Abstract*—A stroke occurs when blood flow to the brain is critically reduced or blocked, potentially resulting in motor paralysis. One of the most promising and effective neurorehabilitation methods for strokes is a closed-loop brain–computer interface (BCI) based on the motor imagery (MI). For the design of MI-based BCI, action observation (AO) during MI facilitates the detection of a user's motor intention. In this paper, we investigated whether or not the AO's targeted objects (the hand of a participant or another person) affects brain activity during MI. To investigate the differences in brain activity induced by the targeted objection, we recorded electroencephalography (EEG) data of 15 healthy right-handed males during three different conditions: 1) MI and AO of a participant's hand (MI + ownAO); 2) MI and AO of a non-participant's hand (MI + otherAO); and 3) MI only. The results showed that the event-related desynchronization (ERD) responses in the alpha frequency band (8–13 Hz) during MI + ownAO over the sensorimotor area (at the C3 and C4 channel locations) were stronger than those during the other two conditions. The results also showed that the difference between the participants' and non-participants' hands affected ERD responses during MI + ownAO and MI + otherAO.**

***Index Terms*—Motor imagery (MI), electroencephalography (EEG), event-related desynchronization (ERD), rehabilitation after stroke, sensorimotor cortex, closed-loop brain–computer interface (BCI).**

I. Introduction

A STROKE occurs when blood flow to the brain is critically reduced or blocked, potentially resulting in motor paralysis. The key to motor recovery is brain plasticity, which lets an uninjured brain region complement the given function of a damaged brain region; therefore, enhanced brain plasticity can lead to motor recovery. Previous studies have reported that brain plasticity is not only promoted not only by involuntary sensory stimulation but also by sensory stimulation with the patient's active attention [1]–[3]. For these reasons motor imagery (MI)-based brain–computer interface (BCI) technology is a novel and effective neurorehabilitation method for stroke rehabilitation training [4]. A closed-loop BCI [4]–[9] can estimate a patient's motor intention from the variations in brain activity over the central area, and it can give the patient visual and propioceptive feedback. A variation is typically observed as event-related desynchronization (ERD), which is short-lasting and circumscribed attenuation in alpha (8–13 Hz) and beta (13–28 Hz) rhythm activities in EEG [10], [11].

ERD is induced by MI, passive action observation (AO), or a combination of the two (MI + AO) [6], [12], [13]. The detection of ERD responses through MI and AO has been incorporated into closed-loop BCI. To devise MI-based BCIs, it is necessary to develop experimental MI setting that can enhance the ERD response.

To determine the best MI-related task for detecting motor intention, various experimental settings have been investigated. One way to enhance ERD responses is to combine MI and AO. Neuper *et al.* [14] investigated ERD responses to MI and MI + AO related to the grasping movement, reporting that no significant differences between MI and MI + AO were observed in the ERD responses of healthy participants. Berends *et al.* [15] investigated ERD responses to the AO and MI + AO of a non-participant's hand given by a video played on a screen, reporting that the ERD responses of healthy participants during MI + AO were stronger than those during individual AOs. Taube *et al.* [16] reported an fMRI study that investigated motor performance in three different conditions: AO+MI, AO, and MI. Their results showed a significant difference between AO+MI and AO. All these studies showed the importance of MI + AO to activate brain regions associated with motor function.

The relationship between AO and motor function has also been investigated. One rehabilitation method for recovery from paralysis after stroke is mirror therapy [17], [18]. Mirror therapy involves the patient placing their responsive limbs on one side of an apparatus and their limbs with hemiplegia on the other side of that apparatus. The patient can see the responsive limb but not the limb with hemiplegia, and a mirror stands on the wall between the limbs, facing the responsive one. Hence, the patient can see the mirror image of their responsive limbs as if the mirror image were their limbs with hemiplegia, which lets the patient imagine motion in the limb with hemiplegia whenever moving their responsive limbs. This therapy can help recover the paretic limb's motor function.

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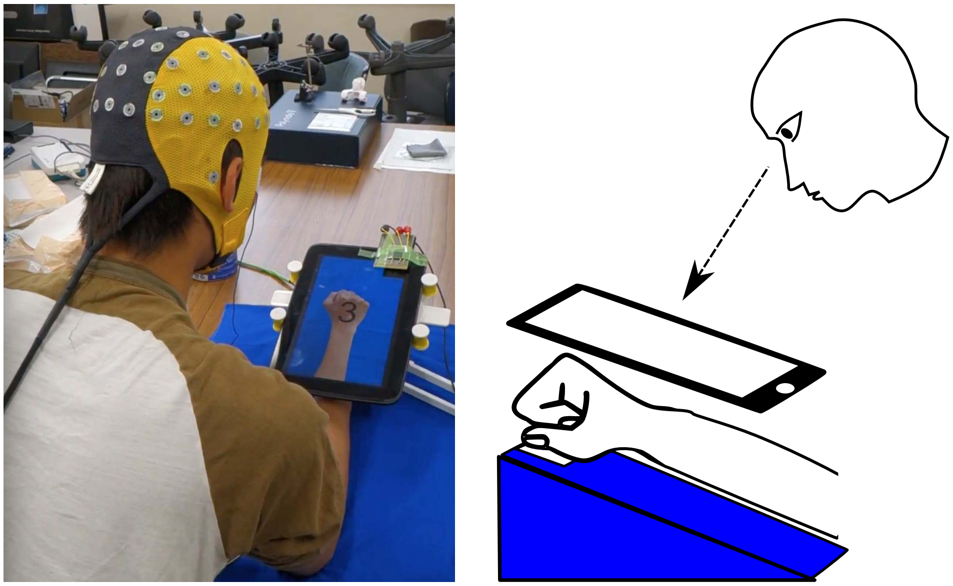


(a) (b)

Fig. 1. Experimental setup. (a) Top view of the experiment. A tablet monitor was placed over the participant's right forearms on the desk in front of them. (b) Diagrammatic view of the experiment from the left. There is a space to open the hand, which made it easier to imagine the opening–clench hand movement.

Harmsen *et al.* [19] investigated the effect of AO training, reporting that stroke patients with paralysis who observed a video of the mirror image of a healthy upper-arm's reaching movement can shorten the time of their upper-arm reaching tasks. Cochin *et al.* [20] investigated cerebral electrical variations from quantified electroencephalography (EEG) while participants observed and executed finger pincer movements with the thumb and index finger. They reported that both observation and execution of finger movements induced ERD in a 7.5–10.5 Hz frequency band. The ERD responses appeared on nine electrode locations (C3, C4, F7, F8, P3, P4, T5, and T6).

Schütz-Bosbach *et al.* [21] suggested that AO's facilitation of the motor system depends on the agent (self or other) to whom the observed action is attributed. Their work investigated whether or not targeted objects (the self's hand or another's hand) affected motor systems with motor evoked potentials (MEPs) induced by transcranial magnetic stimulation during AO. This result suggests that the level of ERD can depend on the agent (self or other) during AO becausethe relationship between ERD and MEP has been shown to exist [22]; a large ERD during wrist motor imagery was associated with significantly increased MEP amplitudes.

As mentioned above, AO and MI have positive effects on rehabilitation from motor paralysis; however, it remains unclear whether or not targeted objection (self or other) affects brain activity during MI + AO. Thus, we hypothesized that ERD responses are different in MI + AO of a participant's hand compared to a non-participant's hand. We focused on ERD responses in the alpha and beta frequency bands, as previous studies reported that ERD responses in the alpha frequency band are more significant in MI than those in the beta frequency band are and can be effectively compared with conditional ERDs [14], [23].

To verify our hypohtesis, we analyzed EEG signals of 15 healthy participants under three different conditions: (1) MI and AO of a participant's hand (MI + ownAO), (2) MI and AO of a non-participant's hand (MI + otherAO), and (3) MI only. Participants were asked to imagine their hand movements in synchrony with the video clip displayed on the monitor and with corresponding speech cues (MI + ownAO and MI + otherAO); they were also asked to imagine opening and closing their hands according to speech cues (MI). In the analysis, the ERD responses were compared among the three conditions.

II. Method

A. Participants

The participants comprised 15 healthy, right-handed males aged 20–24 years (mean age: 22 years). All participants gave their written informed consent. This study was approved by the Research Ethics Committee of Tokyo University of Agriculture and Technology.

B. Experimental Paradigm

To compare the ERD responses induced by different motor tasks, we performed an EEG experiment consisting of three different conditions: MI + ownAO, MI + otherAO, and MI only. During the experiment, participants were seated in a chair with a 10.055-inch tablet monitor (Nexus 10, Google Inc.) placed over their right forearms on a desk in front of them. Fig. 1 illustrates the experimental conditions ((a): view from the top, (b): diagramatic view from the left). A soft, slanted cushion was used to support the participant's arm. There is a space to open the hand because no space around the fist prevented participants from imaging the hand movement. The participants took part in three tasks; Fig. 2 illustrates the trial sequence in the experiment. Each trial comprised *rest*, *preparation*, *task*, and *task interval* periods. Immediately after the rest period (2 s), a picture of a closed hand and the countdown

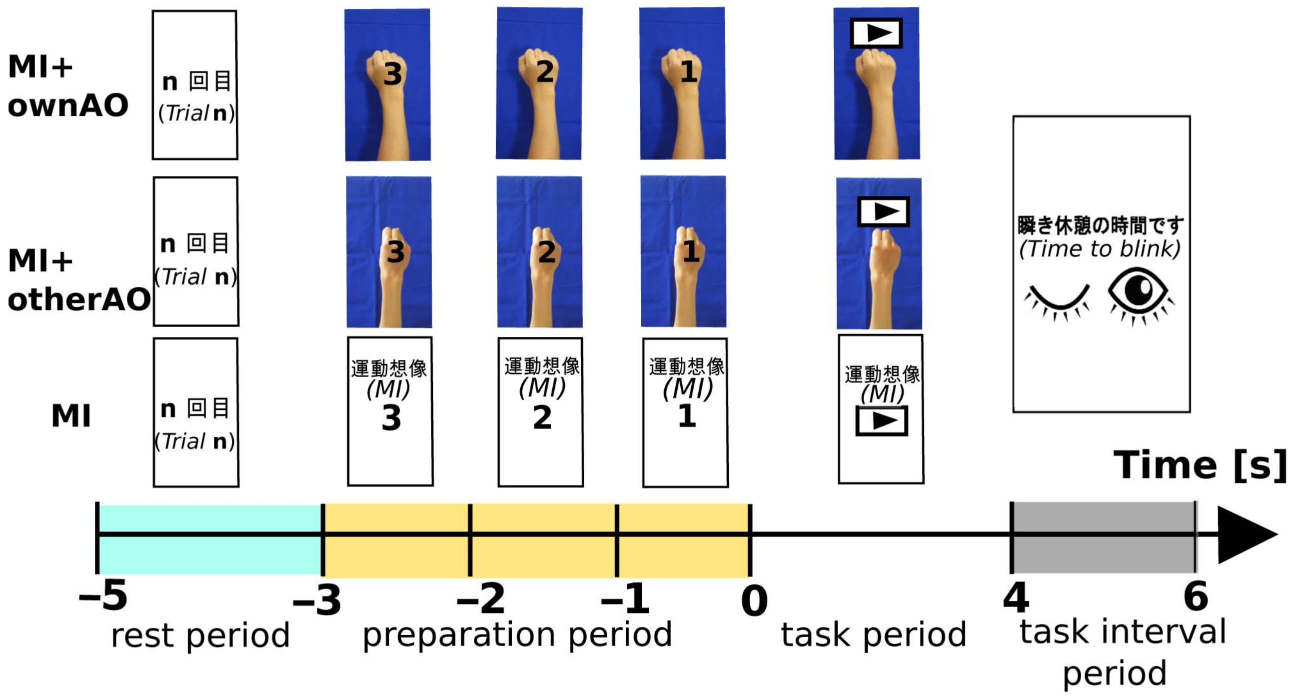


Fig. 2. Experimental flow of the multitask EEG experiment with three different MI conditions: MI + ownAO, MI + otherAO, and MI only.

time (3 s) were displayed on the monitor during the preparation period. Then, during the task period, participants were asked to imagine an open–clench hand movement (4 s), which was the repeated opening and clenching of the right hand according to cues in Japanese speech, "pah" (open) and "goo" (close), given every 1 s. The speech cues were synchronized with the open–clench movement. Subjects were instructed not to blink or move during the trials. Thus, we set the task interval period as a time for the participant to blink and relax (2 s). The fist in the picture started moving for open–clench hand movement in the task period, where participants performed three types of imaginary tasks without moving their own hands (MI + ownAO, MI + otherAO, and MI). In MI + ownAO, participants performed MI while observing an open–clench hand movement video that consisted of a participant's hand movement. In MI + otherAO, participants performed MI while observing an open–clench hand movement video that consisted of a non-participant's (female) hand movement. The purpose of adopting a female as the non-participant was to clarify the differences between the participants' and non-participants' hands. The order of the three conditions (MI, MI + ownAO, and MI + otherAO) was random. The experiment comprised three sessions, which included five trials for each of the three conditions. In total, participants performed 45 trials. The participants were not trained before they started sessions, but they watched the video used in the MI + otherAO as a sample once.

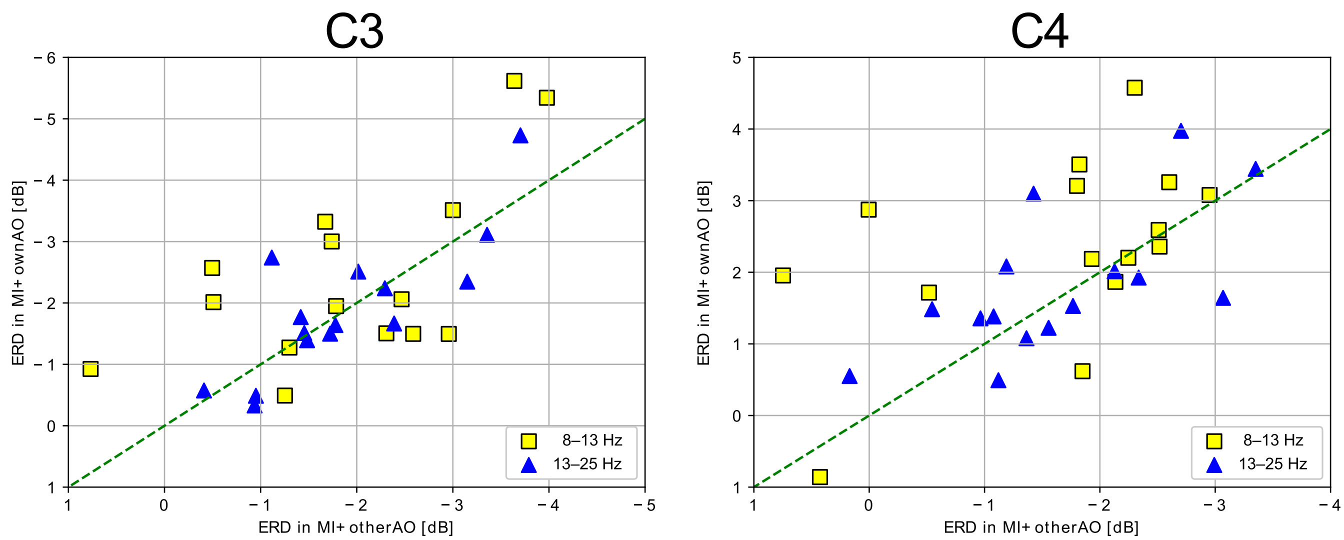
C. EEG Data Recording

During the experiment, EEG signals were recorded using Ag/AgCl passive electrodes embedded in a waveguard cap (ANT Neuro). For recording, 27 electrodes located at Fp1, Fp2, AF3, F3, Fz, F4, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P3, Pz, P4, PO3, PO4, O1, and O2 were used, following the international 1020 system. To check eye movements, electrooculogram (EOG) signals were recorded with an Ag/AgCl flat passive electrode (Nihon Kohden), which was placed to the right of the right eye. To check hand movements, electromyography (EMG) signals were recorded with a pair of passive electrodes over the *extensor digitorum communis* muscle. The GND electrode was located at AFz. The EEG, EOG, and EMG signals were referenced as the average signal recorded between the left and right mastoids leads, and they were amplified by Polymate V (TEAC), which had a band-pass filter of 0.3–333 Hz and an A/D converter with a sampling rate of 1,000 Hz. An APMonitor (TEAC) was used to record the signals.

D. Data Processing and Analysis

The recorded EEG signals were band-pass filtered from 1 to 30 Hz using a zero-phase finite impulse response filter and cut into epochs from −5.0 s to 4.0 s with respect to the onset of the trials. Each epoch was down-sampled from 1,000 Hz to 200 Hz. The extended infomax independent component analysis (ICA) algorithm [24] was applied to the concatenated epochs to separate the independent brain EEG processes from those of artifactual components, such as blinking, eye movement, and muscle activities [25]. After ICA, the independent components were removed based on ADJUST [26]. The epochs were re-referenced for the average signal across all EEG electrodes.

After preprocessing, the short-time Fourier transform with a Hanning window of 0.64 s shifted by a step of 0.04 s was applied to the epochs to obtain the power spectrogram $P(f, t)$.



(a) (b)

Fig. 3. Scatterplot of the ERD strength at C3 (a) and C4 (b) during MI + ownAO and MI + otherAO for all participants for the alpha and beta frequency bands. The dotted line indicates an equal ERD strength for MI + ownAO and MI + otherAO. In other words, points for alpha and beta frequency bands above the dotted line indicate stronger ERD inducted by MI + ownAO, and points for bands below the dotted line indicate stronger ERD induced by MI + otherAO.

The power spectrograms were averaged for each task. ERD was calculated by the following equations [27].

$$P_{\text{rest}}(f) = \frac{1}{|T_{\text{rest}}|} \sum_{t \in T_{\text{rest}}} P(f,t) \quad (1)$$

$$\text{ERD}(f,t) = 10 \log_{10} \frac{P(f,t)}{P_{\text{rest}}(f)} \quad (2)$$

where f, t, and $P_{\text{rest}}(f)$ denote frequency, time, and power spectrum, respectively during the rest period (T_{rest}) between -5 and -3 s from the MI task onset.

E. Statistical Analysis

To investigate the ERD response difference during MI among the conditions, ERD_{MI} over the central area (the electrodes C3 and C4) was statistically analyzed using a three-way repeated measures analysis of variance (ANOVA) at each of the alpha and beta bands. ERD_{MI} was calculated by the following equation.

$$\text{ERD}_{\text{MI}} = \frac{1}{|F|} \frac{1}{|T_{\text{MI}}|} \sum_{f \in F} \sum_{t \in \text{T}_{\text{MI}}} \text{ERD}(f,t) \quad (3)$$

where T_{MI} and F denote the period during MI and frequency bands (alpha or beta), respectively. The within-participants factors were imagery conditions (MI, MI + ownAO, and MI + otherAO), electrodes (C3 and C4), and frequency bands (alpha and beta). Significant interaction effects were followed by tests of the simple interaction effects and the simple main effects. *Post hoc* comparisons were based on the modified Holm's sequentially rejective Bonferroni procedure [28]. The significance level was set at $p < 0.05$.

III. Results

A. ERD Topographical Plots and ERD Time–Frequency Maps

Fig. 3 depicts scatter plots between the ERD in the alpha band (8–13 Hz) and beta band (13–25 Hz) at C3 and C4 during the task period (4 s; from 0 s to 4 s) in MI + ownAO and MI + otherAO for each participant. Fig. 4 shows the topographical plots of the alpha ERD averaged from all participants during the task period. The plots indicate that ERD has mainly been induced around the central area, including electrodes C3 and C4.

Fig. 5 shows the grand mean time–frequency maps at the central and occipital areas (left panels: MI, central panels: MI + ownAO, right panels: MI + otherAO), which were computed by averaging the time–frequency maps of each trial for all participants. The MI onset is at 0 s. The blue suggests an ERD, meaning that the frequency band's power decreases during the MI compared to the baseline (2 s; from -5 s to -3 s). As shown in Fig. 5, the power in the alpha (8–13 Hz) and beta (13–25 Hz) frequencies decreased during MI (4 s; from 0 s to -4 s), especially in the alpha frequency band, and the ERD in MI + AO was stronger than that in MI only. The more significant ERD response during MI in the alpha frequency band compared to the beta frequency band was consistent with Neuper *et al.*'s findings [14]. The power in the alpha frequency also decreased during the time for preparation time (3 s; from -3 s to 0 s). However, Fig. 5 also illustrates similar ERD responses between MI + ownAO and MI + otherAO.

The effects of visual and movement onset stimulations in MI + ownAO and MI + otherAO can be observed as event-related potentials (ERP), the strong amplitude (red-color) in O1 and O2 after $t = -3$ s in a low frequency band (<8 Hz),

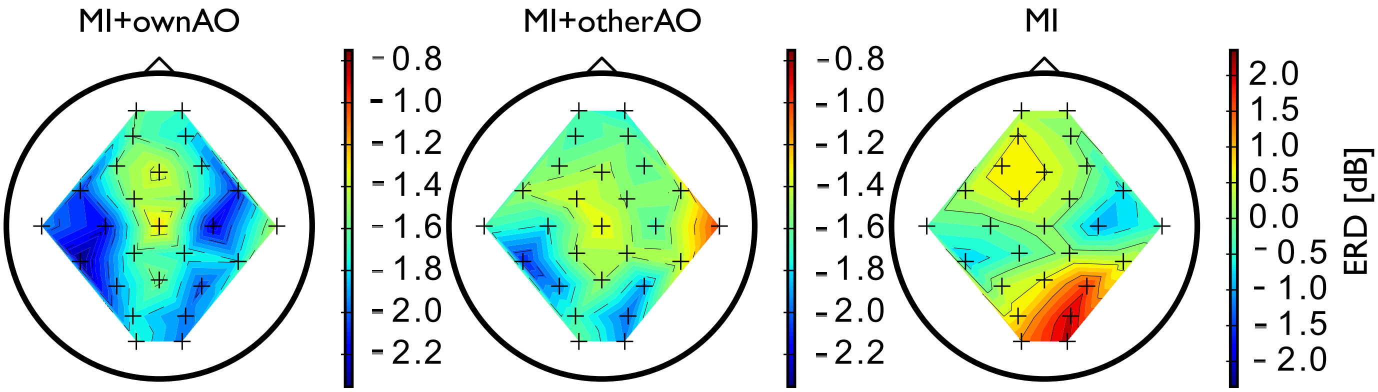


Fig. 4. Topographical plots of the alpha ERD averaged from all participants during MI (0 s < t < 4 s). Red indicates the power increase during the task period compared to the power during the rest period (−5 s < t < −3 s). Blue indicates the power decrease during the task period compared to the power during the rest period.

as illustrated in Fig. 5. This frequency band did not overlap with the alpha band, which was the target of our analysis.

B. ERD Time Course

Fig. 6 shows the ERD time courses derived from each of the three MI conditions. The time courses were plotted in red for the MI + ownAO condition, blue for the MI + otherAO condition, and green for the MI condition. All time courses were computed by averaging the ERD time courses in the alpha frequency band and across all participants.

As shown in Fig. 6, a power decrease occurred at the end of the rest time ($t = -3$ s), especially in the MI + AO condition. During the preparation time (3 s; from −3 s to 0 s), the power decreased relative to the rest time (2 s; from −5 s to −3 s). When MI began ($t > 0$ s), the ERD amplitude became stronger compared to the rest and preparation time. At the onset of MI ($t = 0$ s), the power rapidly decreased in all conditions. Additionally, the abovementioned features were observed more clearly at the C3 channel than at the C4 channel, since the right hand was chosen for open–clench hand movement during MI in this experiment.

C. Results of the Statistical Analysis

First, to investigate the ERD difference in the alpha frequency band between two conditions (MI + ownAO and MI + otherAO), the t-test was conducted for all electrodes. Fig. 7 depicts the electrodes that showed significant differences.

Next, we focused on the central areas (C3 and C4) to see the ERD response difference during the task period among the conditions, conducting a three-way repeated measures ANOVA on the ERD amplitude with the conditions (MI, MI + ownAO, MI + otherAO), the electrodes (C3 and C4), and the frequency bands (alpha and beta). The ANOVA results revealed one main conditional effect, and two significant two-way interactions of condition × frequency and condition × electrode. No other effects were significant (all $p > 0.05$).

The main conditional effect was significant: $F(2, 28) = 13.260$, $p = 0.0001$. *Post hoc* tests revealed that the ERD amplitudes during MI in MI + ownAO (-2.397 ± 1.368) were significantly greater than that in only MI, and those in MI + otherAO (-1.770 ± 1.207) were also significantly greater than those in MI only (-0.560 ± 1.266) ($p < 0.01$). No significant ERD amplitude difference during MI was observed between MI + ownAO and MI + otherAO. These results indicate that the ERD responses induced by MI + AO were greater than those induced by MI only over the sensorimotor area.

The condition × frequency interaction was statistically significant: $F(2, 28) = 8.491$, $p = 0.0013$. For the alpha band, the main conditional effect was significant: $F(2, 28) = 12.80$, $p = 0.0001$. The *post hoc* tests revealed that the ERD during MI + ownAO and MI + otherAO was significantly stronger than that during MI only ($p = 0.0007$ and $p = 0.0096$, respectively), while the ERD during MI + ownAO was significantly stronger than that during MI + otherAO ($p = 0.0301$). These results are summarized in Fig. 8 as box plots, indicating the difference between a participant's and a non-participant's hand, which was used as the target for AO affected ERD responses in MI + AO. Moreover, the participant's own hand for AO could strengthen the ERD response during MI more effectively than the non-participant's hand could. For the beta band, the main conditional effect of condition was significant: $F(2, 28) = 6.34$, $p = 0.0054$. The *post hoc* tests revealed that the ERD during MI + ownAO and MI + otherAO was significantly stronger than that during MI only ($p = 0.0077$ and $p = 0.0060$, respectively). However, no significant difference in the ERD occurred between MI + ownAO and MI + otherAO ($p = 0.66$).

The condition × electrode interaction was statistically significant: $F(2, 28) = 4.4668$, $p = 0.0207$. For the C3, the main conditional effect was significant: $F(2, 28) = 16.7819$, $p = 0.0000$. The *post hoc* tests revealed that the ERD during MI + ownAO and MI + otherAO was significantly stronger than that during MI only ($p = 0.0003$ and $p = 0.0007$, respectively), but no significant ERD difference was observed between MI + ownAO and MI + otherAO. For the C4, the main conditional effect was significant: $F(2, 28) = 5.6155$, $p = 0.0089$. The *post hoc* tests revealed that the ERD during MI + ownAO was significantly stronger than that during MI only ($p = 0.0110$). No other significant ERD difference was observed.

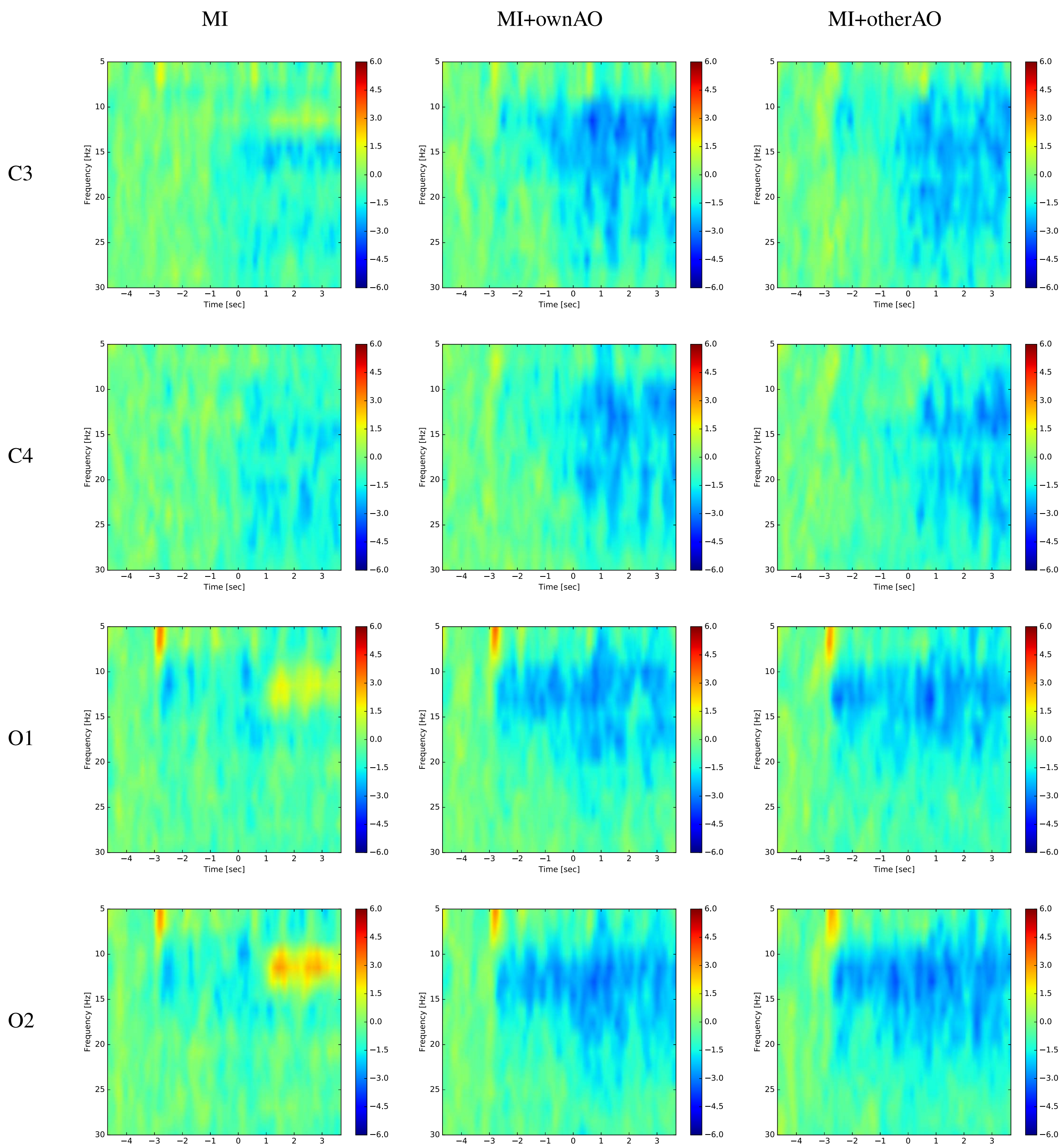


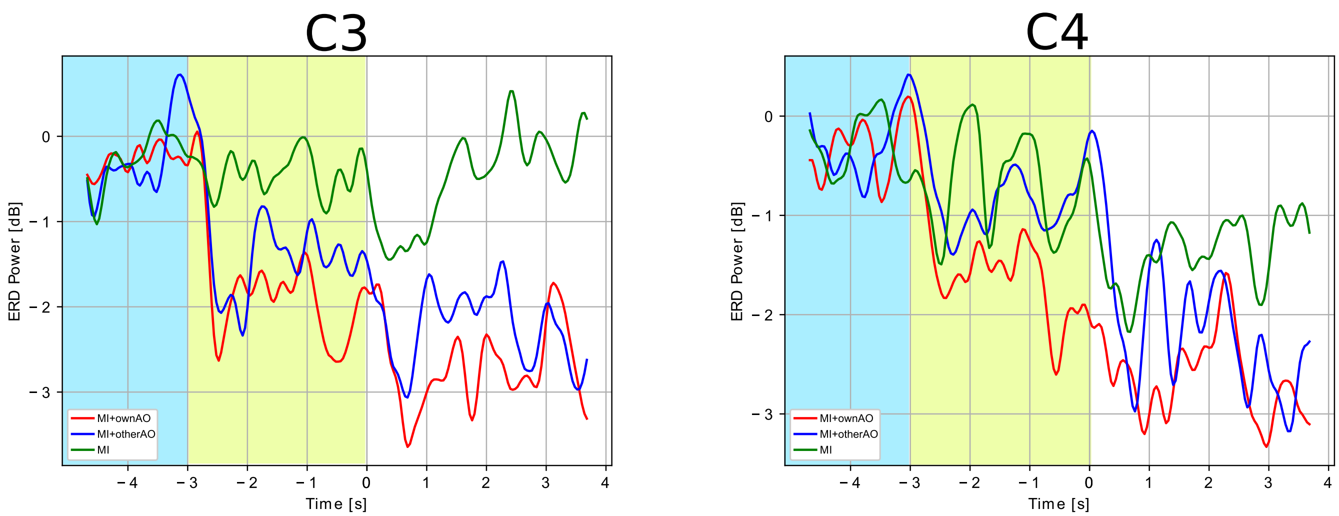
Fig. 5. A grand mean time–frequency map of ERD at the sensorimotor area (left panels: MI, center panels: MI + ownAO, right panels: MI + otherAO), which was computed by averaging the time–frequency maps of each trial for all participants. The onset of MI is at 0 s. Blue indicates an ERD; the frequency bands' power decreased during the MI compared to the baseline (2 s; from −5 s to −3 s). During MI (4 s; from 0 s to 4 s), a clear ERD response was found in the alpha frequency band (8–13 Hz).

IV. Discussion

In this paper, we hypothesized that ERD responses are different in MI + ownAO and MI + otherAO. To verify our hypothesis, we recorded EEG data and calculated ERD during three different conditions: (1) MI + ownAO, (2) MI + otherAO, and (3) MI only. Results showed that the ERD responses in the alpha frequency band during MI + ownAO at the C3 and C4 channel locations were stronger than those during the other two conditions.

A. Topographic Maps of the Alpha ERD

The power in the alpha frequency band over the central area and occipital area strongly decreased during MI for both MI + ownAO and MI + otherAO. We also observed the



(a) (b)

Fig. 6. The grand mean alpha ERD time courses in the alpha frequency band (8–13 Hz) range ((a): C3, (b): C4). The first 2 s (right blue area) indicate the rest period; the next 3 s (right yellow area) indicate the preparation period. At $t = -3$ s, the picture on the monitor changed from the trial number to the hand picture. At $t = 0$ s (MI onset), the picture switched to the open–clench hand movement video. The conditions' ERD time courses were plotted in red (MI + ownAO), blue (MI + otherAO), and green (MI), and were computed by averaging the ERD time courses in the alpha frequency band and across all participants for each task.

power suppression in the alpha frequency band over the central area for MI only; however, the power increased in the alpha frequency band over the occipital area. Many researchers have reported the relationship between MI and ERD, where the alpha ERD induced by MI is mainly observed over the central area, and our observed power decrease in the alpha frequency band over the central area during MI in all conditions was consistent with those findings.

B. ERD in the Central and Occipital Areas

In terms of the alpha ERD over the occipital area, Eaves *et al.* [29] reported that MI + AO conditions for ERD in the occipital area, which correspond to the visual cortex, were stronger than they were for the conditions in both pure AO and pure MI. Moreover, da Silva [30], Chatrian *et al.* [31], and Pfurtscheller and Berghold [32] reported that alpha ERD reflects a state of cortical activation containing a characteristic to plan or prepare for movement. Some researchers claimed that alpha ERD over the visual cortex is related to visual imagery, and there is a possibility that some participants unintentionally followed visual imagery, even when being instructed to follow kinesthetic cues. However, Neuper *et al.* [33] reported that the ERD responses during kinesthetic cues were found to be close to the sensorimotor hand area, whereas visual MI did not show a clear spatial pattern. According to Fig. 5, the time–frequency spectrogram exhibited alpha ERD around the central area (C3 and C4), which shows that the participants in this experiment might have done kinesthetic imagery as instructed. From what has been discussed above, we can deduce that the videos included in MI + ownAO and MI + otherAO to depict the open–clench hand movement activated the visual cortex; therefore, we observed stronger alpha ERD in MI + ownAO and MI + other AO than in MI only, which only used a still picture of a hand.

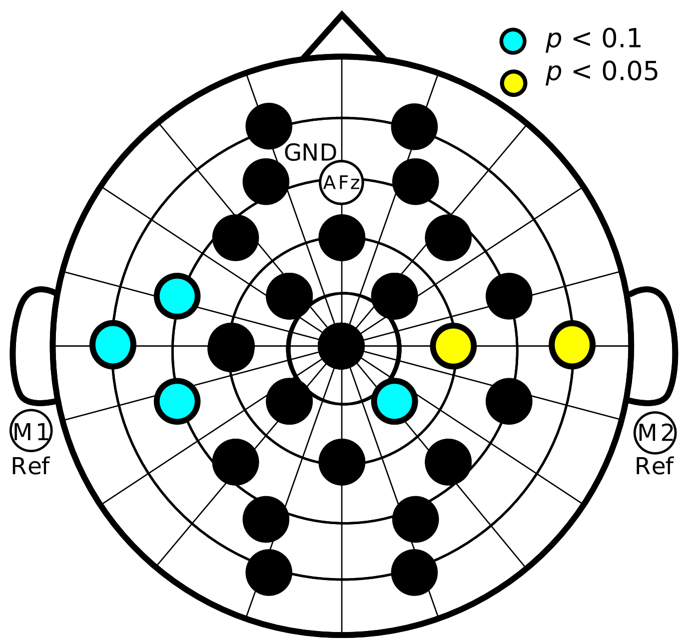


Fig. 7. The t-test was conducted for all electrodes. The light blue and yellow circles indicate the significant differences in alpha ERD between MI + ownAO and MI + otherAO ($p < 0.1$ and $p < 0.05$, respectively).

C. MI + OwnAO vs. MI + OtherAO

According to the statistical analysis results shown in Fig. 8, the ERD for MI + ownAO and MI + otherAO is stronger than that for only MI. This result is also supported by the past EEG study with stroke patients [34] reporting that the ERD for MI with AO was stronger than that for MI. Considering the previous studies [15], [16] that showed MI with AO is better than AO in ERD, we can deduce that MI with AO is effective in enhancing ERD, compared to either MI or AO only.

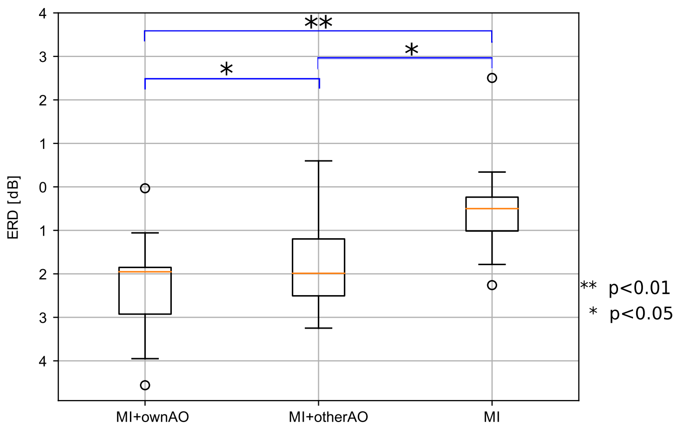


Fig. 8. The results of the three-way ANOVA for the alpha band. The ERD box was collapsed across the C3 and C4 electrodes for the 15 participants. Statistical significance is indicated by asterisks ($^{**}p < 0.01$, $^{*}p < 0.05$).

Our hypothesis was verified by the ERD responses in the alpha frequency band during MI + ownAO over the central area stronger than those during MI + otherAO. The reason for this observation could be familiarity. Some researchers have investigated the effects those familiarity on brain activity and have discovered that the central area activity weakens when observing unrealistic movements, such as those performed by robots [35], [36], and animals movements [37] that are impossible for humans to perform [38], [39]. In particular, Ulloa and Pineda [39] reported that a point-light biological motion produced the mu (alpha) suppression. This may explain why ERD in only the alpha band showed strong ERD during MI + ownAO; however, as shown in Fig. 5, clear ERD was observed in both alpha and beta bands, which may support the previous report in the case of realistic visual feedback with the participant's hand [40].

Thus, it is possible that the shortage of familiar shapes (the participant's hand or another's hand) induced the different ERD responses among the MI conditions. In this experiment, the potentially familiar factors were the beating sounds and the shape of the hand. Participants were seated in a chair, and a 10.055-inch tablet monitor was placed over their right forearms on a desk in front of them. Then, their MI was conducted according to cues in Japanese speech, "pah" (open) and"goo" (close), given every 1 s. It is possible that some patients did not feel familiar with the hand shown in the video and the cued timing for open–clench movement.

These results indicate that the difference between a participant's and a non-participant's hand as the AO target affects ERD responses in MI + AO. In conclusion, we recommend the use of a video of each patient's own extremity in the design of a closed-loop BCI with an AO condition.

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