1. INTRODUCTION

Although the recognition of visual objects is often performed using purely visual features such as shapes [1-3], both the recognition and the imagining of familiar artifactual objects are often accompanied by the activation of motion-related regions. This pairing is thought to reflect the retrieval of stored motion semantics associated with objects [4, 5]. For example, the perception of a tool is often accompanied by the pattern of activation in the motor-related area seen when that tool is being used [6, 7]. Likewise, the observer’s knowledge about how a tool is manipulated under normal circumstances has been reported to modulate both behavioral responses to visually presented tools [8-10] and neural responses in the motor- and object-related areas that respond to the category of the tools [11]. Research on letter processing has uncovered a similar phenomenon. Perception of letters tends to be accompanied by the pattern of activation in the motor-related area seen when those letters are being written [12, 13]. These findings suggest that kinesthetic information can be invoked by, and in turn exert influence over, the process of visually distinguishing objects belonging to one category (e.g., tools) from objects belonging to another (e.g., animals).

According to one school of thought, the mirror neuron system plays an essential role in our ability to understand others’ actions and their traces. On this type of account, the activation of motor-related regions during the observation of others’ actions or their traces can be viewed as a result of the activation of the mirror neuron system, which is thought to underlie our ability to imitate others’ actions.

The primary aim of this study is to examine whether and how motor-related “experience” associated with objects modulates neural responses in the sensorimotor circuit when objects are visually recognized with the intention to imitate the actions that created those objects. To achieve that goal, we investigated how the motor cortex is activated in healthy young adults while they are observing familiar and unfamiliar handwritings. We found that the motor cortex tended to show more pronounced activation when the participants saw handwritings written by others rather than by themselves, and when they saw types of strokes that they were accustomed to writing. These findings suggest an interplay between perception and memorized action in the visuo-motor system.
of recorded EEG oscillations were evaluated. An event-related relative decrease in the power of a frequency band indicates event-related desynchronization (ERD) and an increase in the band power indicates event-related synchronization (ERS). The ERD of the alpha and beta oscillations is interpreted as a correlate of an activated cortical region and the quantification of the ERS and ERD mappings in time and space can be used to study the dynamics of cortical activation patterns [16-18].

In the experiment, we had participants stare at several different graphemes one at a time and copy each onto a tablet. We then examined whether the motor-related region was activated to different degrees while the participants were only looking at, not copying, those graphemes. Specifically, the following four types of stimuli were used in the two-way factorial design: mastered graphemes (radicals used in real characters) written by the participants themselves, mastered graphemes written by someone else, unmastered graphemes (graphemes that look like but are different from radicals that are used in real characters) written by the participants themselves, and unmastered graphemes written by someone else. We expected that the observation of the mastered graphemes would induce a level of activation in the motor-related regions higher than that induced in the observation of unmastered graphemes. We also predicted that the observation of graphemes written by the participants themselves would involve a level of activation in the motor-related region higher than that involved in the observation of graphemes written by others. These predictions were based on our hypothesis that subjects’ own handwriting is associated with motor programs with which they have considerable experience, whereas others’ handwriting is not.

The graphemes used in our experiment included Chinese radicals—that is, components that recur in many Chinese characters and are likely to have associated implied motor programs. However, it is important to note that they are not pronounceable. We chose these graphemes to rule out the possibility of motor-related areas being activated by the process of inner articulation.

The dorsal parieto-frontal pathway is known to regulate attention and process kinesthetic information [19, 20]. Therefore, we also attempted to determine whether activation in motor-related areas was due to the processing of kinesthetic information or regulation of attention.

2. METHODS

2.1 Participants

Sixteen healthy adults (seven females; mean age 20.3 years; standard deviation [SD], 1.38 years) with normal or corrected-to-normal vision took part in this study and received a financial compensation for their time. They were naïve to the purpose of the experiment. (There were four more participants but they were excluded from the analysis owing to artifacts related to eye blinks, muscle activity, skin potentials such as sweating, or poor behavioral performance.) All participants were students at the University of Tokyo and strongly right-handed according to an assessment using the Edinburgh Handedness Inventory [21]. Their native language was Japanese and they had no neurological diseases or history of reading or writing disorders or other language disabilities. All experimental procedures were carried out in accordance with the Helsinki Declaration 2000 and approved by the local ethics committee at the University of Tokyo.

2.2 Stimuli

Participants were exposed to four types of visual stimuli. The experiment had a two-level factorial design in which independent variables were mastery (mastered vs. unmastered) and agency (own-produced vs. other-produced):

(a) own-produced, mastered real radicals;
(b) other-produced, mastered real radicals;
(c) own-produced, unmastered pseudo-radicals;
(d) other-produced, unmastered pseudo-radicals.

Radicals are component parts of Chinese characters, whereas pseudo-radicals are strokes that resemble real radicals but are not contained in any Chinese characters. More specifically, the pseudo-radicals were created from real radicals by moving one or two lines to wrong positions based on methods described in previous research [22, 23]. Note that we expected the real radicals used in the experiment to be mastered strokes for all Japanese adults because they are contained in many of the Chinese characters taught in primary schools. Fig. 1 shows examples of the four types of stimuli.

Forty-eight real radicals and 48 pseudo-radicals were used. Statistical analyses of the computer-generated real radicals and pseudo-radicals in terms of radial spatial frequencies revealed no significant differences between

![Figure 1: An example of stimuli.](image-url)
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All radicals were presented centrally in white against a black background, and each participant performed a total of 384 trials. The period subjected to analysis with regard to the modulation of neural responses in motor-related areas was from 100 ms prior to the presentation onset of the objects to 1850 ms after the onset, and does not include the time spent for copying. Participants were asked to keep their limbs still during the observation, which lasted randomly for 2000 ± 150 ms. After copying, an interval that lasted randomly for 3000 ± 150 ms occurred. Each participant was fully trained in the task before its execution during the experimental trials.

2.3 Procedure

A handwriting session without EEG recording was held prior to the experimental session to obtain the participants’ handwritings to be presented to them in the experimental session. In the handwriting session, the participants sat approximately 57 cm from a display monitor and transcribed at their own pace each single radical presented on the monitor onto a 50 mm × 50 mm square on a sheet of paper. Individual real radicals and pseudo-radicals were presented centrally in black against a white background, and subtended approximately 9° × 9° of visual angle.

Approximately one week later, the experimental recording session took place, in which the participants sat approximately 57 cm from the display monitor with a digital tablet and a pen. Because (as noted in the Introduction) the question we intended to address was how the neural responses in the sensorimotor circuit is modulated when objects are visually perceived with the intention to imitate the actions that produced them, participants were shown graphemes one at a time and instructed to copy each of them onto the tablet at their own pace after it disappears from the display. While copying, the participants’ written responses on the tablet were projected online on the display. To avoid activation of the participants’ motor cortex caused by their observation of their limbs, their hands were obscured from their fields of view. All radicals were presented centrally in white against a black background in a dimly lit room and subtended with approximately 2° × 2° of visual angle.

Participants were exposed to the four experimental stimuli described above. The radicals and pseudo-radicals used in the one’s own handwriting condition were the samples written by the participant himself or herself in the handwriting session, whereas the radicals and pseudo-radicals used in the others’ handwriting condition were a set of handwritings written by an individual randomly chosen from the other participants. The order of stimulus condition was pseudo-randomized and 96 trials were recorded for each condition. Although stimuli of the four types were mixed within a session, the experiment was divided into four blocks that lasted no more than 10 min each to avoid participants’ fatigue. Participants were encouraged to take a short break between blocks. The order of the blocks was counterbalanced between the participants and each participant performed a total of 384 trials.

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2.4 Data acquisition

Recording of EEG data. All recordings took place in a dimly lit, sound-attenuated room. EEG activity was recorded using Active Two amplifier (BioSemi, Amsterdam, Netherlands) and 32-channel Ag/AgCl pin-type scalp electrodes referenced to the common mode sense-driven right leg ground, which formed an internal feedback loop driving the average potential across the montage as close as possible to the zero level with the amplifier. To monitor the undesired artifacts of eye and hand movements online, we acquired electro-oculographic (EOG) activity, using two additional flat electrodes placed below and at the outer canthi of the right eye, and electromyographic (EMG) activity using another bipolar Ag/AgCl surface electrode from the flexor pollicis brevis of the right hand. The analog signals of the EEGs were digitized at 1024 Hz with a 0.1–100 Hz online bandpass filter. Because the BioSemi Active Two system uses active electrodes in order to ensure an optimal signal-to-noise ratio, and each electrode contains a preamplifier, electrode impedances have not been measured with the electrodes. The electrode offset was kept to < 20 µV, as recommended for the system amplifiers.

Epoching of EEG data. Recorded EEGs were first desampled to 512 Hz using EEGLAB [24] for independent component analysis (ICA) [25]. Further, the retained EEG data was re-referenced offline with the channel placed on the nose tip and segmented into 1.85-s epochs including a 100-ms pre-stimulus baseline period. The pre-stimulus period of -100 ms to 0 ms was used as a baseline to correct event-related potential (ERP) epochs lasting 1850 ms, which were later averaged.

Artifact detection and correction. Computerized artifact rejection was used to discard epochs in which eye movements or muscle artifacts led to EEG amplitudes of > 500 µV and abnormal trends with slopes of > 250 µV per epoch. Other artifact correction/removal related to eye blinks, muscle activity, and skin potentials such as sweating were made using the independent component analysis filter in the EEGLAB toolbox [26, 27]. For example, we removed an ICA component, which was identified as eye blinks according to the EEGLAB wiki (http://sccn.ucsd.edu/wiki/Chapter_09:_Decomposing_Data_Using_ICA)
when the montage showed a strong far-frontal projection and the smoothly decreasing EEG spectrum typical of eye artifacts.

Data analysis. To evaluate the dynamics of levels of activation in the motor-related area across conditions, we assessed oscillatory signal changes of each condition in the beta band over the primary motor cortex (M1) in two temporal epochs. We chose this approach because these signals over M1 contralateral to moved limbs are known to be generated in the premotor and primary sensori-motor areas [28, 29] and the M1 area consistently modulates its rhythmic activities after voluntary finger movements, passive movements elicited by electric median nerve stimuli, or observation of others’ actions [16, 29-31]. When a movement is made or observed, the frequency power spectrum relative to that in the baseline period undergoes suppression (known as ERD) in both the beta and alpha bands over the M1 for several hundreds of milliseconds, followed by rebound to a level of above the resting level (known as ERS) peaking around 1000 ms after the movement or observation.

The average time course of relative changes in the EEG frequency spectrum induced by experimental events of the four conditions was computed using an event-related spectral perturbation (ERSP) method [32]. To compute an ERSP, baseline spectra are calculated from the EEG immediately preceding each experimental event (-100 ms to 0 ms). The epoch was divided into brief, overlapping data window, and a moving average of the amplitude spectra of these was created. These spectral transforms of individual response epochs are then normalized by dividing them by their respective mean baseline spectra. Normalized response transforms for many trials are then averaged to produce an average ERSP. Based on the assumption that the degree to which the spectral power in the beta band over the M1 is suppressed is proportional to the degree to which the M1 area is activated, we assessed oscillatory signal changes of each condition in successive temporal epochs to indicate the degree of cortical activation, following the method used in [33]. Because the ERD of the alpha and beta oscillations is interpreted as a correlate of an activated cortical with increased excitability, the more the rebound is suppressed (and hence the smaller the ERS/ERD is), the more the area is activated.

The selection of the location of the electrode, the range of frequency band, and temporal epochs were consistent with those adopted in previous studies [29-31, 34]. The channel relevant to M1 is defined as C3 in a 10–20 standard system in the contra-lateral hemisphere to the right hand. The frequency band of interest was beta band defined as 15–23 Hz. Two temporal epochs (400–1000 ms and 50–300 ms) were chosen for the calculation of ERS and ERD respectively.

To determine whether the activation in C3 was due to the processing of kinesthetic information or the regulation of attention, the amplitude over Pz according to a 10–20 standard system was measured and compared between conditions. The larger amplitude of the late positive component in the parietal lobe is believed to be related to greater attention allocation [35-37].

Statistical analysis. Proportions of frequency spectrum of individual data were further statistically analyzed and each condition was compared using 2 × 2 repeated measures analysis of variance (ANOVA). To quantify the effects of different character conditions on the scalp channel ERPs, we analyzed comparisons of grand-averaged ERPs using t-test functions in EEGLAB.

3. RESULTS

3.1 Enhanced activation in motor-related area

Fig. 2 shows the grand-averaged EEG beta band signals and ERSP spectrogram over the C3 electrode for a representative participant under the four stimuli conditions. In the latter analysis, dark areas indicate low power spectrum whereas bright areas show high power spectrum. The time 0 corresponds to the onset of the presentation of stimuli. White-bracketed areas are intervals and frequency bands of interest that depict a rough picture of the ERD and ERS.

Fig. 3 reports the mean of ERS/ERD over the C3 electrode for 16 participants between two stimuli conditions. Error bars indicate standard errors of the mean over the sampling distribution. Our results according to two factorial repeated measured ANOVA showed that the main effect of mastery conditions was significant (F[1,15] = 5.89, p < 0.028, partial η² = 0.62). Moreover, the main effect of agency conditions was significant (F[1,15] = 5.11, p < 0.039, partial η² = 0.56). However, the mastery × agency interaction did not reach statistical significance (p > 0.189), suggesting that the mean of ERS/ERD under each agency condition (two levels of agency) was unaffected by mastery of the target stimuli. Fig. 3 shows that the mean of ERS/ERD over C3 in the observation of unmastered graphemes was significantly lower than that in the observation of mastered graphemes. Likewise, the mean of ERS/ERD over C3 in the observation of other-produced graphemes was significantly lower than that in the observation of own-produced graphemes.

In contrast with the distinct temporal beta band signal changes over C3 under the four stimuli conditions, those over Pz were unaffected by stimuli conditions. Two-way
repeated-measures ANOVA showed that the main effect of mastery conditions did not reach statistical significance ($F[1,15] = 1.59, p > 0.226, \text{partial } \eta^2 = 0.10$). Likewise, the main effect of agency conditions ($F[1,15] = 3.25, p > 0.092, \text{partial } \eta^2 = 0.18$) and the mastery × agency interaction ($F[1,15] = 1.21, p > 0.288, \text{partial } \eta^2 = 0.08$) did not reach statistical significance.

### 3.2 Attention-related late positive components in Parietal Cortex

Figures 4 and 5 show comparisons of the grand-averaged amplitudes of scalp ERPs over Pz between mastery conditions and between agency conditions, respectively. In both comparisons, a larger attention-related positive slow wave of an ERP component peaking around 500–1000 ms after the onset of stimulus presentation occurs under all conditions. Statistical analyses suggested that the amplitudes of those attention-related late positive components were significantly differentiated around 500–1500 ms between agency conditions and around 1000 ms between mastery conditions. In comparisons of agency conditions, the amplitude under the own–handwriting condition (peak amplitude, 19.8 $\mu$V; latency, 529 ms) was larger than that under other–handwriting condition (peak...
amplitude, 12.9 µV; latency, 480 ms), whereas in comparisons between mastery conditions, the amplitude under the mastered condition (peak amplitude, 18.4 µV; latency, 528 ms) was larger than that under the unmastered condition (peak amplitude, 13.9 µV; latency, 482 ms).

Larger amplitude of early positive components was observed around 100–200 ms for mastered grapheme condition and statistical analyses suggested that the amplitudes of early positive components were significantly differentiated between mastery conditions. This might be related to greater attention allocation for known graphemes. Previous studies suggest that attention allocation onto object features in general [38] and onto well-learned categories of visual objects such as orthographically regular letters [39–41] can enhance a positive brain potential component that appears 100–200 ms after the stimulus onset.

Grand-averaged amplitudes of scalp ERPs over C3 showed that the positive slow wave of an ERP component over C3 peaking around 500–1000 ms after the onset of stimulus presentation was shallower and later in its latency than those over Pz under all conditions, suggesting that the positive slow wave did not originate in C3.

4. DISCUSSION

The suppression of beta-rebound rhythms in the EEG response over C3 was, contrary to our hypothesis, pronounced during subjects’ observation of both unmastered handwriting and others’ handwriting. Because suppression of the beta band rhythm indicates induced (non-phase-locked) ERD, which is a correlate of an activated cortical area with increased excitability, the above results suggest that the motor-related region was activated to a greater degree during the observation of unmastered and others’ handwriting.

The results of our experiment appear to suggest that the object (in particular letter) recognition process proceeds not only on the basis of the visual properties of the objects and some kinesthetic information associated with the object but also relying on subtle kinesthetic information to distinguish unmastered from mastered handwriting and others’ handwriting from a subject’s own handwriting, which are based on the experience or motion repertoire of observers. One interpretation is that the motor-related region is activated to a greater degree during the observation of unmastered handwriting with the intention to imitate it because the recognition of letters that the participants were unaccustomed to writing enforces difficult encoding and motor planning for the upcoming imitation task and possibly requires the process of simulating the writing of those letters in the motor-related area (more than that required for the recognition of letters that the participants were accustomed to writing).

Likewise, the motor-related region may have been activated to a greater degree during the observation of others’ handwriting than during the subjects’ observation of their own handwriting because the recognition of their own handwriting could be performed through the retrieval of stored motor programs rather than through simulation in the motor-related area. Thus, the results of our experiment can be understood in terms of the extent to which the motor-related area was recruited to encode, plan and perhaps perform simulation of upcoming writing movements. Furthermore, the present results allow us to conclude that the motor-related area is activated during the observation of static handwritten letters even when the observation is unaccompanied by inner articulation because the visual stimuli used were unpronounceable.

As noted in the Introduction, because the dorsal pathway—which regulates the motor system—is known to regulate attention, the possibility remains that the increased activation over C3 during the recognition of others’ handwriting was due to increased demand for the regulation of attention rather than increased demand for the encoding, planning and processing of kinesthetic information for the upcoming imitation task. Such an alternative interpretation, however, is ruled out by the following hypothesis. If motor-related area is activated as a result of the attention-demanding nature of a task, the subjects’ recognition of other’s handwriting could be accompanied by parietal lobe activation stronger than that accompanying the recognition of their own handwriting. This hypothesis, however, is contradicted by our result: the subjects’ observation of their own handwriting, not the observation of other’s handwriting, induced the higher level of activation in the parietal lobe. The late positive components that occurred during the subjects’ observation of their own handwriting were larger than those accompanying their observation of other’s handwriting, as was seen in a previous study under similar experimental settings [42]. This result is consistent with the widely accepted view that self-related stimuli in general attract greater attention [37, 43–46]. Late positive components accompanying the observation of unmastered handwriting seemed to be larger than those accompanying mastered handwriting, but the difference was smaller during the period of interest.

5. CONCLUSIONS

To summarize, we conducted an EEG experiment to investigate how healthy young adults recognize the traces or trajectories of actions with an intention to imitate them,
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with a special focus on the question of whether the motor cortex would be activated by perceptions of handwritings, which are by definition traces of hand movements. Participants wrote two types of components of Chinese characters—mastered and unmastered—and were later shown various handwritten strokes written by themselves or by others and then copied them. We found that the motor cortex displayed more pronounced activation when the participants looked at handwriting by others and unmastered strokes. These findings suggest an interplay between perception and memorized action in the visuo-motor system and add to our knowledge about higher-order representation in object recognition that is performed in preparation for imitation tasks.

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