

Temporal changes of beta rhythms and rotation-related negativity reflect switches in motor imagery*

Hiroshi Yokoyama¹, Isao Nambu¹, Jun Izawa², and Yasuhiro Wada¹

Abstract—While motor imagery has been known as a powerful tool for neuro-rehabilitation in stroke patients, whether this technique is also effective for other brain disorders is unclear. For instance, patients with Parkinson’s disease or attention-deficit hyperactivity disorder who are impaired at real motor switching may benefit therapeutically from training that consists of switching their imagined motor movements, and eventually recover from the dysfunction. However, despite its importance little is known about exactly how switching mental images of one’s actions is processed in the brain. Therefore, we set out to clarify this issue by measuring brain activity reflected in electroencephalograms as subjects switched an imagined hand rotation from one hand to the other during a motor-imagery task. By comparing electroencephalogram signals from repeated mental imaging of hand movements, we found a switch-specific decrease in the beta-band activity in parietal and frontal regions around 0.6 s after stimulus presentation. Further, we found rotation-related negativity in the parietal cortex at the same time as the decreased beta-band power. These results suggest that the parietal area is dynamically involved in the switching of imagined hand motion, and that frontal areas may have an important role in inhibiting mental imagery of the deselected hand’s motion.

I. INTRODUCTION

Motor imagery refers to imagining one’s own motor movements without any motor execution, and has been used in studies of neuro-rehabilitation with stroke patients. It has been studied as an effective strategy to train stroke patients to recover their motor function because simply imagining their actions can engage their brains’ intact sensory-motor systems [1]. We theorized that this strategy of rehabilitation without action might be effective therapy for other brain disorders. For instance, as patients with Parkinson’s disease and attention-deficit hyperactivity disorder have dysfunctions in motor switching, a training program that consists of switching their imagined actions might help them to recover from this impairment[1]. However, while motor imagery has been studied, little is known about exactly how switching mental images of one’s actions is processed in the brain.

Critically, the area responsible for switching motor images is unknown. A study using functional magnetic resonance imaging with Parkinson’s disease patients revealed increased activity in the pre-supplementary motor area (pre-SMA) when switching actions during a mental hand-rotation

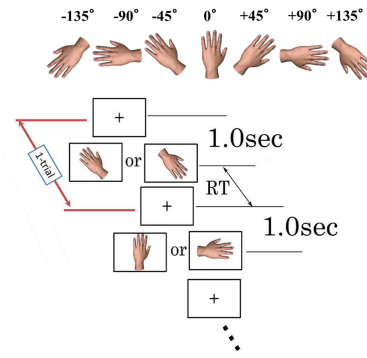


Fig. 1. Experimental paradigm.

task, suggesting a possible role for the pre-SMA in motor switching [4]. However, because action selection and execution are performed continuously within a very short time period, functional magnetic resonance imaging with its poor temporal resolution is not a recommended technique to study switching motor imagery. Thus, we measured brain activity evoked by a mental hand-rotation task using electroencephalograms (EEGs) that have superior temporal resolution.

Our objective here was to find a neural correlate of the switch between motor imagery of the left and right hands. To this end, we investigated information processing in the brain by measuring EEG signals while participants performed a mental rotation task to clarify the dynamical activity of motor switching. Specifically, we compared event-related desynchronization (ERD) [2][3] and rotation-related negativity (RRN) [9][10] from trials in which participants imagined the same hand’s motion in the previous trial (Repeat trials) with those in which they imagined the other hand’s motion in the previous trial (Switch trials) when they were asked to judge a hand-laterality of the presented hand-images. While this task requires a cognitive processing, it also leads the participants to engage in motor imagery [4].

II. EXPERIMENTAL METHODS

A. Participants

This study was approved by the ethics board of the Nagaoka University of Technology. Seven right-handed healthy men (range: 23-25 years, mean: 23.5 years) participated in the experiment after having given written informed consent.

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¹H. Yokoyama, I. Nambu and Y. Wada are with the Electrical Engineering, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka, Niigata, 940-2188, Japan h_yokoyama@stn.nagaokaut.ac.jp

²J. Izawa is with the NTT Communication Science Laboratories, 3-1, Morinosato Wakamiya Atsugi, Kanagawa, 243-0198, Japan

B. Experimental paradigm

Participants sat in a chair placed in front of a PC monitor. They were instructed to fixate a point presented at the center of the display. The visual stimuli were images of left and right hands, and were presented to participants as depicted in Fig. 1. Visual stimuli were presented once per trial. When participants stepped on a pedal, the visual stimuli disappeared, and the fixation point was presented for 1 s before the next trial began. Participants were shown rotated hands that were selected randomly from one of 14 hand images. The 14 images were made by rotating images of each hand from -135° to $+135^\circ$ in seven steps of 45° . We define the 0° reference angle as a hand with all fingers pointing up.

Motor imagery was induced by asking participants to report whether the visual stimulus was a right or left hand by stepping on a foot pedal as quickly as possible. Then, participants were instructed to use the ipsilateral foot to the presented hand image when they step on a foot pedal to report hand laterality. By using the foot pedal, we aimed to separate brain activity evoked by motor imagery from that evoked by motor execution. The previous studies with the same mental hand-rotation task showed that alpha and beta power ERD reflect cognitive process of implicitly evoked internal hand movement in contralateral sensorimotor area to the selected hand image while performing this task [2][3].

We randomly presented visual stimuli in 112 trials per session, so that the hand angle and laterality were counter-balanced (seven trials for each of the 14 hands). We measured EEGs with 64 channels (Active Two; Biosemi, Amsterdam, The Netherlands; sampling frequency: 1024 Hz) on the scalp.

C. Behavioral data

The difference in behavioral performance between Switch and Repeat trials was evaluated by reaction time (RT). The RT was measured as the time required to judge hand laterality of the visual stimuli, and was defined as the time from stimulus onset until the participants stepped on the pedal. We averaged RT across participants for each hand angle. Then, differences in RT between Switch and Repeat trials for each angle were compared quantitatively to evaluate the time required for information processing during the two conditions.

D. EEG data analysis

Previous studies using mental rotation tasks have suggested that neural activity underlying mental rotation of hands is reflected in a specific decrease of EEG rhythm in the premotor cortex [3] and a specific decrease in event-related potential in the parietal cortex that increases in latency (between 0.5 and 0.8 s) as the angle of the presented hand increases away from vertical (the RRN) [9][10]. We therefore evaluated EEG rhythm and ERPs to detect the neural activity associated with motor-imagery switching that underlies the mental hand-rotation task.

a) **Time-frequency analysis:** We calculated time-frequency power in the beta band (20-25 Hz) to demonstrate temporal localization of a specific frequency band corresponding to switch-related activity in motor imagery. In the analysis, we calculated the changes in frequency power from the baseline period (event-related spectral perturbation: ERSP) to evaluate the time-frequency response associated with the conditions. We used the wavelet algorithm of the EEGLAB (<http://sccn.ucsd.edu/eeglab/>) toolbox for Matlab. We tested the calculated ERD with a two-way analysis of variance (ANOVA) with trial type (Repeat or Switch) and hand angle (-135° , -90° , -45° , 0° , $+45^\circ$, $+90^\circ$, or $+135^\circ$) as factors. Mean ERSP data were calculated for each of ten 0.1 s epochs beginning at stimulus onset and compared with an ANOVA.

b) **Rotation-related negativity:** We evaluated the RRN[9][10] by comparing grand means of ERPs across all participants between small- (0°) and large- ($\pm 135^\circ$) rotation trials in both Switch and Repeat trials. First, we calculated the grand mean of brain electric potentials across all participants using a filtered EEG signal with a zero phase-shift butterworth filter (cutoff frequency: 1-12 Hz) for each participant. Next, we calculated the ERPs using the grand mean of the filtered EEG signal across all participants for each hand angle. Then, to quantitatively evaluate the difference in RRN between Switch and Repeat trials, we compared the ERP waveforms between small- and large-rotation trials for both Switch and Repeat trials with a two-sample t-test for each epoch from 0 to 1.0 s using the mean ERPs for each participant. In doing so, we aimed to detect a switch-specific waveform in the EEG signal.

III. RESULTS

A. Behavioral data

The averaged RT across participants for each presented angle is shown in Fig. 2. RT was observed to increase with hand angle (away from 0°). This finding agrees with that of another study [5], which indicates that participants were engaged in mental rotation of hands: When participants are requested to answer which hand is being presented, they naturally imagine rotating their left or right hand and determine whether the shape of the imagined hand matches the shape of the presented image.

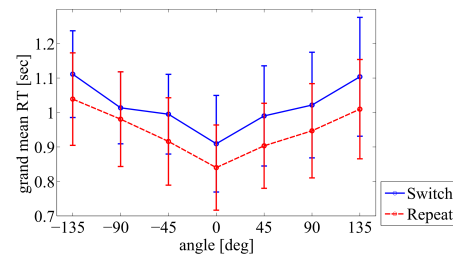


Fig. 2. Grand mean of RT.

The average RT in Switch trials was larger than those in Repeat trials, and differences in RT between the trial types appeared constant irrespective of the angle. To evaluate these trends quantitatively, a two-way ANOVA was conducted with trial type (Switch or Repeat) and angle (-135° , -90° , -45° , 0° , $+45^\circ$, $+90^\circ$, or $+135^\circ$) as factors. Significant main effects were found for both factors (trial type: $p = 0.0079$; angle: $p = 0.0056$), but not for their interaction ($p = 0.9945$). Moreover, we performed additional two-way ANOVAs to test whether the hand (left or right) or angle affected RT for in each trial type (Switch and Repeat). No significant difference was observed for the hand type (Switch trials: $p = 0.6087$; Repeat trials: $p = 0.8093$) but one was observed for the angle (Switch trials:

$p = 0.0147$; Repeat trials: $p = 0.0035$). No significant interaction between hand and angle was observed (Switch trials: $p = 0.9644$; Repeat trials: $p = 0.7267$) was found. These behavioral results suggest some difference in how motor imagery is processed during Switch and Repeat trials, regardless of the amount of rotation or the hand being imagined.

B. Time frequency analysis

Fig. 3 shows the spatial localization of significant differences in each epoch for the beta-band between Switch and Repeat trials. Significant differences were localized at F5 in Epoch 1 ($p < 0.01$), at Pz in Epochs 3, 7, and 8 (Epochs 3 and 7: $p < 0.05$, Epoch 8: $p < 0.01$), and at F8 in Epochs

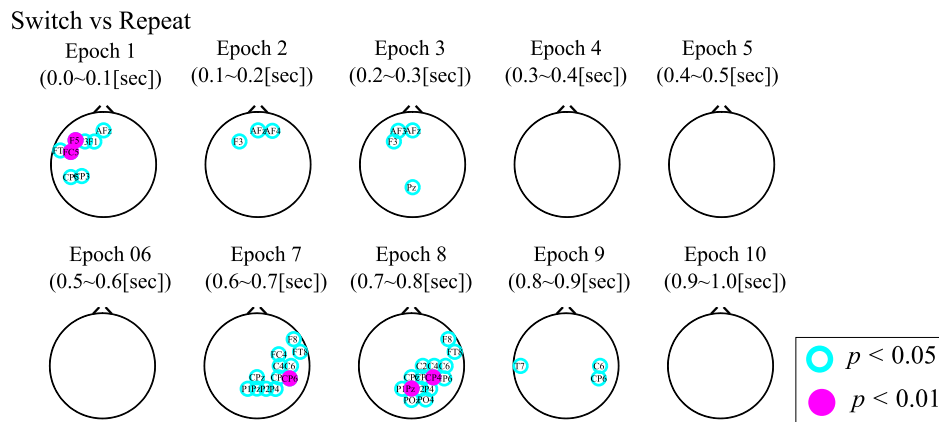


Fig. 3. Temporal localization of statistically significant differences in beta-power ERS between Switch trials and Repeat trials, separated by epoch.

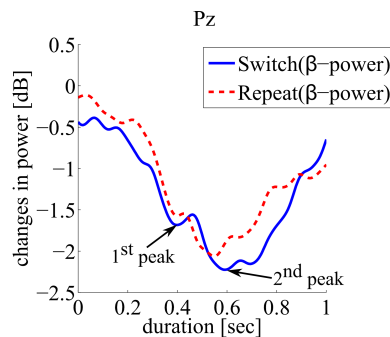


Fig. 4. Grand-mean of ERS (Pz, beta-band: 20-25 Hz).

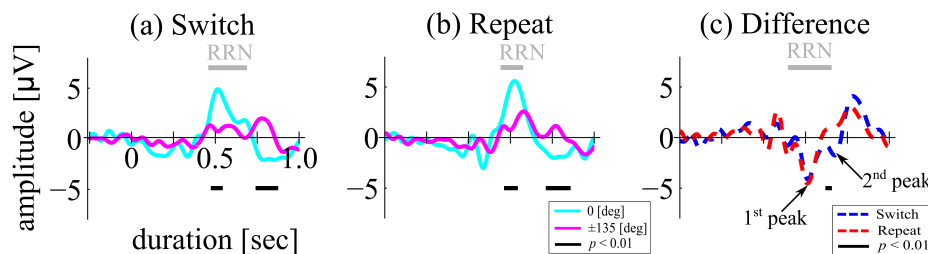


Fig. 5. Grand mean of ERPs in the Pz channel.

7 and 8 ($p < 0.05$). F5 is the channel corresponding to the PFC, a region related to cognitive switching [8] and working memory load [11]. F8 corresponds to the inferior frontal gyrus (IFG), an area that has been suggested to be involved in motor inhibition [6]. Pz corresponds to posterior parietal cortex (PPC), which is associated with decisions related to selective working memory [7]. Statistically significant differences were seen at Pz in two distinct periods: an interval from 0.2 to 0.3 s corresponding to Epoch 3 and another from 0.6 to 0.7 s corresponding to Epochs 7 and 8. Fig. 4 shows the grand mean ERSP at Pz calculated across participants. While Repeat trials showed a time-frequency response with a single ERD peak from 0.4 to 0.6 s (Epochs 5 and 6), Switch trials showed a time-frequency response with two ERD peaks at intervals that agreed with the above-mentioned timing of statistically significant differences at Pz. These two peaks in beta-power ERD at Pz might therefore be associated with the switching of motor imagery.

Meanwhile, we tested other frequency band (theta: 4-8Hz, alpha: 8-12Hz) by same token, nevertheless other band has no significant difference such as beta band.

C. Rotation-related negativity

We calculated grand ERP means to evaluate differences in RRN between Switch and Repeat trials. First, as shown in Fig. 5a and b, we found an RRN in the ERP waveform at Pz that was greater on large-rotation trials than short-rotation ones. This RRN occurred 0.5 s after stimulus onset, around the time of the two ERD peaks in both Switch and Repeat trials (see the interval shown by the gray solid line). ERPs between small- and large-rotation trials were compared by two sample t-test, and results showed statistically significant differences ($p < 0.01$) during intervals that were consistent across trial types (see the interval shown by the black solid line in Fig. 5a and b).

Second, we found a switch-specific waveform around the time of the later ERD peak by comparing differences in waveforms during small- and large-rotation trials across trial type (Fig. 5c). The difference in waveforms for Switch trials has two negative peaks with nearly the same timing as those of the two ERD peaks (Fig. 4), with the second peak being statistically significant ($p < 0.01$).

D. Summary

We found switch-specific decreases in EEG beta-band activity that peak in both the parietal and frontal cortex. Moreover, the switch-specific ERP (RRN) had two peaks in parietal cortex that occurred around the same time that beta-band activity decreased. These decreases in activity suggest dynamic involvement of the parietal area when switching motor imagery of the hands, an interpretation that is consistent with reports indicating that alpha- and beta-band power over parietal regions are involved in mental imaging of hand rotation [2] and that a specific ERP negativity is assumed to be involved in deciding which hand in mental imagine of hand rotation [9][10].

In addition, the present data indicates two different cognitive processes. First, we found significant switch-related activity in channel F5, which corresponds to left-IFG, around 0.0-0.1 s after onset of the visual stimuli. This fact suggests that higher load to access the working memory is required in switch trial [11]. Second, we found significant switch-related activity in channel F8, which corresponds to right-IFG. Because IFG has an important role in motor inhibition [6], we can suppose that this type of motor-switching task is performed in part by inhibiting motor imagery of the unselected hand.

IV. CONCLUSIONS

We found specific switch-related activity reflected in beta-power ERD around 0.6-0.7 s after onset of the visual stimuli. These ERDs were localized approximately to the PPC and IFG. Additionally, we observed switch-specific ERPs that were localized approximately to the PPC at occurred at about the same time as the switch-related ERD activity. This suggests dynamic involvement of the parietal cortex in switching imagined hand motion between hands. By providing online biofeedback of these signals to patients we may be able to facilitate their ability to switch between real motor tasks.

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REFERENCES

- [1] J.J. Daly, J.R. Wolpaw: Brain.computer interfaces in neurological rehabilitation. *The Lancet Neurology*. **7** (2008), 1032-1043
- [2] X. Chen, G. Bin, I. Daly, X. Gao: Event-related desynchronization (ERD) in the alpha band during a hand mental rotation task. *Neuroscience Letters*. **541** (2013), 238-242
- [3] A.C. Ter Horst, B.V. Lier, B. Steenbergen: Mental rotation strategies reflected in event-related (de)synchronization of alpha and mu power. *Psychophysiology*. **50** (2013), 858-863
- [4] R.C. Helmich, E. Aarts, F.P. de Lange, B.R. Bloem, I. Toni: Increased dependence of action selection on recent motor history in Parkinson's disease. *The Journal of Neuroscience*. **13** (2009), 6105-6113
- [5] L.A. Cooper, R.N. Shepard: Mental transformation in the identification of left and right hands. *Journal of Experimental Psychology*. **1** (1975), 48-56
- [6] A.R. Aron, R.A. Poldrack: Cortical and subcortical contributions to stop signal response inhibition: Role of the subthalamic nucleus. *The Journal of Neuroscience*. **9** (2006), 2424-2433
- [7] M.E. Berryhill, E.B. Wencil, H.B. Coslett, I.R. Olson: A selective working memory impairment after transcranial direct current stimulation to the right parietal lobe. *Neuroscience Letters*. **479** (2010), 312-316
- [8] T.S. Braver, J.R. Reynolds, D.I. Donaldson: Neural Mechanisms of Transient and Sustained Cognitive Control during Task Switching. *Neuron*. **39** (2003), 713-726
- [9] Z.C. Thayer, B.W. Johnson: Cerebral processes during visuo-motor imagery of hands. *Psychophysiology*. **43** (2006), 401-412
- [10] M. van Elk, C. Crajé, Manuela E. G. V. Beeren, B. Steenbergen, H. T. van Schie, H. Bekkering: Neural evidence for compromised motor imagery in right hemiparetic cerebral palsy. *Frontiers in Neurology*. **1** (2010), 150-156
- [11] D. Tomasia, L. Chang, E.C. Caparelli, T. Ernst: Different activation patterns for working memory load and visual attention load. *Brain Research*. **1132** (2007), 158-165