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# Neuroanatomical correlates of brain–computer interface performance

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ABSTRACT

Brain–computer interfaces (BCIs) offer a potential means to replace or restore lost motor function. However, BCI performance varies considerably between users, the reasons for which are poorly understood. Here we investigated the relationship between sensorimotor rhythm (SMR)-based BCI performance and brain structure. Participants were instructed to control a computer cursor using right- and left-hand motor imagery, which primarily modulated their left- and right-hemispheric SMR powers, respectively. Although most participants were able to control the BCI with success rates significantly above chance level even at the first encounter, they also showed substantial inter-individual variability in BCI success rate. Participants also underwent T1-weighted three-dimensional structural magnetic resonance imaging (MRI). The MRI data were subjected to voxel-based morphometry using BCI success rate as an independent variable. We found that BCI performance correlated with gray matter volume of the supplementary motor area, supplementary somatosensory area, and dorsal premotor cortex. We suggest that SMR-based BCI performance is associated with development of non-primary somatosensory and motor areas. Advancing our understanding of BCI performance in relation to its neuroanatomical correlates may lead to better customization of BCIs based on individual brain structure.



## Introduction

Brain–computer interfaces (BCIs) have been studied for their applicability to neuroprostheses as well as a possible neural therapy to induce beneficial plastic changes for rehabilitation (Shindo et al., 2011). Studies have demonstrated the efficacy of motor imagery-induced event-related desynchronization (ERD) of the mu rhythm, or sensorimotor rhythm (SMR), in controlling electroencephalography (EEG)-based BCIs (McFarland et al., 1997, 2005; Neuper et al., 2006; Pfurtscheller et al., 2006). The SMR is an alpha-range EEG oscillation recorded from the central areas, and its ERD is induced by motor execution, motor imagery, or motor observation (Neuper et al., 2005).

Although the SMR-based BCI is one of the most widely used non-invasive BCIs, performance varies considerably between individuals as well as between sessions by the same individual (Wolpaw et al., 2002). Only a handful of studies have investigated correlates of inter- and intra-individual variability in BCI performance. Function-based predictors of BCI performance include SMR amplitude at rest (Blankertz et al., 2010) and concentration level (Hammer et al., 2012). Using functional magnetic resonance imaging (MRI), BCI performance has also been found to correlate with activity in supplementary motor and prefrontal areas during a motor imagery task (Halder et al., 2011). This finding is consistent with neurophysiological studies showing that non-primary motor areas are involved in motor preparation and/or planning (Hoshi and Tanji, 2004). It is also consistent with previous neuroimaging studies on motor imagery, which revealed the premotor-parietal network to be an underlying substrate of motor imagery and motor planning (Hanakawa et al., 2003, 2008).

Structural measures from brain MRI may also offer a means to predict BCI performance. In fact, fractional anisotropy derived from diffusion tensor MRI for the cingulum, superior fronto-occipital fascicle, and corpus callosum have shown efficacy in predicting BCI performance (Halder et al., 2013). Moreover, burgeoning evidence indicates that inter-individual variability of performance in cognition (Frangou et al., 2004; Maguire et al., 2000), language (Hosoda et al., 2013), and movement (Steele et al., 2012; Tanaka et al., 2013) correlate with gray matter volume in an ability-specific manner, although correlation of gray matter volume with BCI performance has yet to be identified. Based on these previous findings, we hypothesized that gray matter volume, especially that of non-primary motor and prefrontal areas (Halder et al., 2011), could be used to predict BCI performance. To test this hypothesis, we performed a whole-brain voxel-based morphometry (VBM)

*Abbreviations:* BCI, brain–computer interface; PMd, dorsal premotor cortex; EEG, electroencephalography; ERD, event-related desynchronization; MRI, magnetic resonance imaging; MIQ-R, revised movement imagery questionnaire; SMA, supplementary motor area; SMR, sensorimotor rhythm; SSA, supplementary somatosensory area; VBM, voxel-based morphometry.

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(Ashburner and Friston, 2000) analysis on healthy participants and examined the relationship between performance using an SMR-based BCI and gray matter volume.

## Methods

### *Participants*

Thirty healthy adults (14 males and 16 females, mean age ± standard deviation: 22.4 ± 3.1 years) participated in this study. All participants were right-handed as assessed by the Edinburgh Inventory (Oldfield, 1971), had normal or corrected-to-normal vision, reported no history of neurological or psychological disorders, and had no prior experience using BCIs. All participants gave informed consent before the experiment according to the study protocol approved by the ethics committee of the National Center of Neurology and Psychiatry. Motor imagery ability was assessed with a Japanese translation of the revised Movement Imagery Questionnaire (MIQ-R) (Hall and Martin, 1997).

### *EEG acquisition*

Electrophysiological data were acquired using BrainAmp amplifiers and an EEG cap (Brain Products, Gilching, Germany) consisting of 12 electrodes, nine positioned over the sensorimotor area (F3, F4, C3, C4, Cz, P3, P4, T7, and T8), one over the left eye (Fp1), one for ground (AFz), and one for reference (FCz). Electrode impedances were kept below 15 kΩ, excluding 10 kΩ of resistance built into the system. To rule out potential influence by overt movements, electromyograms (EMG) over the left and right thenar eminences and horizontal electrooculograms (EOG) were also simultaneously acquired. Data were sampled at 5000 Hz and filtered with 0.1-Hz highpass and 250-Hz lowpass hardware filters. A 1–23 Hz bandpass filter (12th order elliptic) was then applied in software to reduce high-frequency noise and baseline drift. The EEG data were fed into BCI2000 software, which was used to control the experiments (Schalk et al., 2004).

### *BCI experiment*

Participants underwent a BCI experiment in which visual feedback was provided online (Fig. 1A). During each trial, a red rectangular target appeared in the lower right, lower left, or entire bottom portion of the display, signifying a Right trial, Left trial, or control trial, respectively. After 1 s, a cursor appeared horizontally centered at the top of the screen and immediately began falling at a constant rate, such that it would reach the bottom in 4 s. During the Right and Left trials, participants were instructed to perform imagery of finger-thumb opposition with the right and left hands, respectively, to control the horizontal positioning of the cursor so that it would hit the target at the bottom. Participants were instructed to use, to best of their ability, kinesthetic rather than visual imagery (Neuper et al., 2005). They also practiced the movements in response to the cues overtly before engaging in the experiment. During the control trials, participants were asked to passively watch the visual cues on the display. During this period, participants continuously received visual feedback from the falling cursor in all trials. A 1-s result presentation interval followed, during which the cursor and target would turn yellow in the case of a successful trial, or remain unchanged otherwise. After a 1-s inter-stimulus interval with a blank screen, the next trial would begin. Trials were organized in a block design (Fig. 1B), with each block consisting of three trials of the same task. A run consisted of 11 pseudo-random permutations of Right and Left blocks interleaved with 12 control blocks (33 Right trials, 33 Left trials, 36 control trials). Each run began and ended with a control block. The first block of each task was used for initialization of BCI2000's normalization transform (McFarland et al., 2011) and discarded, leaving a total of 30 Right, 30 Left, and 33 control trials per run. Participants performed two runs: one practice run followed by one test run. Each run lasted 12 min. Between runs, participants were allowed to take a break for a few minutes. Further analyses were performed on results from the test run, unless otherwise indicated. BCI success rate was calculated from the number of right-target and left-target hit trials over all Right and Left trials.

### *Online EEG processing*

EEG data were downsampled to 500 Hz, and electrodes over the sensorimotor area were re-referenced to large Laplacian derivations for the C3 and C4 electrodes. Spectral amplitudes for C3 and C4 were then computed using autoregressive estimation (Marple, 1987; McFarland et al., 1997) with a window length of 500 ms and a bin width of 3 Hz. For the BCI experiment, we selected the 9.5–12.5 Hz bin for feature extraction in all participants, allowing the BCI to be controlled with SMR spectral amplitude (Pfurtscheller and Lopes da Silva, 1999). We decided to use this single, predetermined alpha frequency band for BCI control through several pilot measurements in which we consistently found imagery-related ERD for our BCI system. A control signal for cursor movement was computed from the difference in SMR amplitudes for C4 and C3, where greater ERD in C4 resulted in leftward cursor movement and greater ERD in C3 resulted in rightward cursor movement online.

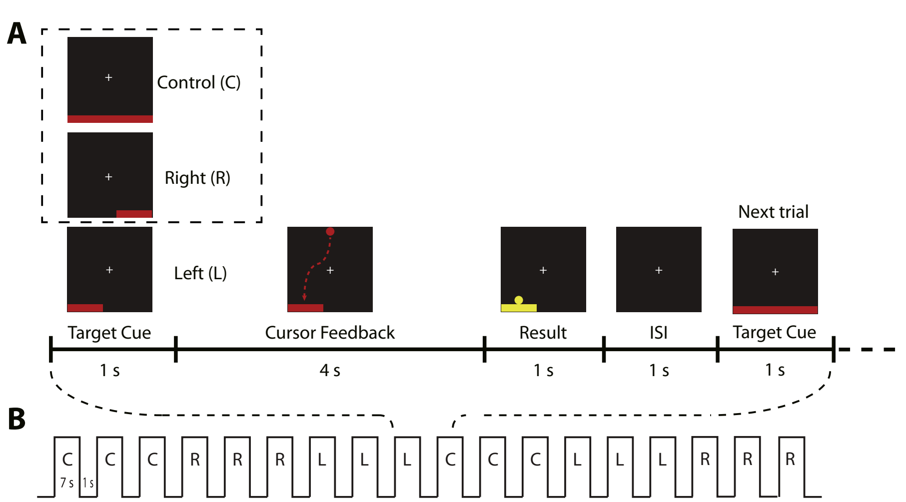


**Fig. 1.** BCI experiment paradigm. ***A***, Visual stimuli and durations for an example Left (L) trial. ***B***, An example trial order for the three tasks. ISI: interstimulus interval, R: Right, C: visuospatial control.