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Laterality of brain activity during motor imagery is modulated by the provision of source level neurofeedback

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ABSTRACT

Motor imagery (MI) may be effective as an adjunct to physical practice for motor skill acquisition. For example, MI is emerging as an effective treatment in stroke neurorehabilitation. As in physical practice, the repetitive activation of neural pathways during MI can drive short- and long-term brain changes that underlie functional recovery. However, the lack of feedback about MI performance may be a factor limiting its effectiveness. The provision of feedback about MI-related brain activity may overcome this limitation by providing the opportunity for individuals to monitor their own performance of this endogenous process. We completed a controlled study to isolate neurofeedback as the factor driving changes in MI-related brain activity across repeated sessions. Eighteen healthy participants took part in 3 sessions comprised of both actual and imagined performance of a button press task. During MI, participants in the neurofeedback group received source level feedback based on activity from the left and right sensorimotor cortex obtained using magnetoencephalography. Participants in the control group received no neurofeedback. MI-related brain activity increased in the sensorimotor cortex contralateral to the imagined movement across sessions in the neurofeedback group, but not in controls. Task performance improved across sessions but did not differ between groups. Our results indicate that the provision of neurofeedback during MI allows healthy individuals to modulate regional brain activity. This finding has the potential to improve the effectiveness of MI as a tool in neurorehabilitation.

Introduction

The acquisition of a motor skill is achieved through alterations in brain activity that occurs as a result of practice (Boe et al., 2012; Doyon and Benali, 2005; Halsband and Lange, 2006). While physical practice is the foundation for motor skill acquisition, motor imagery (MI), the mental rehearsal of physical tasks in the absence of overt muscle contraction (Jeannerod and Frak, 1999), has been shown to be an effective adjunct for skill acquisition in numerous disciplines (Arora et al., 2011; Lebon et al., 2010; Schuster et al., 2011). The similarity in spatial activation patterns observed in the brain between real and imagined movement provides the basis for understanding why MI is an effective adjunct to physical practice (Lacourse et al., 2005; Miller et al., 2010; Orr et al., 2008). Specifically, the repetitive activation of neural pathways during MI forms the basis for short- and long-term plasticity that underlies motor learning (Nudo and Milliken, 1996; Nudo et al., 1996). In addition to facilitating skill acquisition in sport and other skilled motor tasks, MI is emerging as a useful adjunct treatment in neurorehabilitation (Barclay-Goddard et al., 2011; Braun et al., 2006). In particular, MI can be coupled with standard therapies in individuals with upper limb (UL) dysfunction post-stroke to better support functional recovery (Nilsen et al., 2010; Page et al., 2011; Riccio et al., 2010). Coupling MI with standard therapies used in stroke rehabilitation can aid recovery in patients with a range of UL impairment (e.g., good, little or no UL function) owing to the low intensity of resources and decreased physical 'cost' required to perform MI (Barclay-Goddard et al., 2011; Braun et al., 2008; Page et al., 2007).

An essential component of skill acquisition is the provision of feedback (Newell, 1991; Newell and Ranganathan, 2009; Winstein, 1991). Feedback permits the assessment of actual versus planned performance, including the identification and correction of errors (Salmoni et al.,

Abbreviations: ECD, equivalent current dipole; EEG, electroencephalography; EMG, electromyography; ERS, event-related synchronization; ERD, event-related desynchronization; fMRI, functional magnetic resonance imaging; HPI, head position indicator; LME, linear mixed-effects; MEG, magnetoencephalography; MI, motor imagery; SEF, somatosensory evoked field.

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1984; Schmidt, 1976). An individual performing MI does not receive feedback however, limiting their knowledge of if, and how well, they are imagining the movement. Thus, the effectiveness of MI may be limited by the lack of feedback. This limitation could be overcome by the provision of feedback to the individual via real-time depiction of the brain activity underlying performance. Further, region-specific neurofeedback could also prove helpful in guiding an individual to modulate the activity of particular brain regions. This feature would be particularly salient in rehabilitative applications, where emerging evidence indicates that the laterality of brain activity parallels the degree of achievable functional recovery (Askim et al., 2009; Chieffo et al., 2013; Dong et al., 2006).

Numerous studies have shown that individuals receiving neurofeedback based on sensor-level analysis of magneto- or electro-encephalography (MEG and EEG respectively) data can modulate task-related brain activity over repeated sessions (Bai et al., 2014; Buch et al., 2008; Ono et al., 2013; Soekadar et al., 2011). While effective for some applications, sensor-level analysis lacks the spatial specificity needed for applications requiring neurofeedback from targeted brain regions. This level of spatial specificity however can be achieved using neurofeedback based on source level brain activity. For example, Florin and colleagues recently demonstrated the use of neurofeedback derived from real-time source level analysis of MEG data to successfully modulate activity in selected brain regions (Florin et al., 2013). This work builds on previous source level neurofeedback studies demonstrating modulation of alpha band power fluctuations (Sudre et al., 2011) and increased coherence between two distinct cortical regions (Ora et al., 2013). Similarly, the provision of neurofeedback using real-time functional magnetic resonance imaging (fMRI) has enabled the modulation of brain activity in a region-specific manner including the primary motor cortices (Chiew et al., 2012; deCharms et al., 2004) and anterior cingulate (Caria et al., 2007; deCharms et al., 2005).

It is known that repetition of a task is sufficient to drive changes in brain activity. Neurofeedback studies that do not include a control group who perform MI without neurofeedback cannot disentangle neurofeedback-induced changes in brain activity from the aforementioned practice effect. As such, the inclusion of a no feedback control group is necessary to establish the critical role of neurofeedback in driving changes in brain activity. The lack of a control group in source level MEG or EEG studies creates a knowledge gap related to the role of neurofeedback. Filling this knowledge gap would provide key evidence for the role of MI with neurofeedback in facilitating changes in brain activity.

The present study aimed to identify neurofeedback as the factor driving changes in brain activity during MI. We examined the effect of neurofeedback from the left and right sensorimotor cortex, compared to a no feedback control group, on brain activity underlying MI. A secondary objective was to determine if neurofeedback led to greater improvement in the actual performance of the task being imagined. To achieve these objectives, subjects performed actual and imagined movements over three consecutive days. We hypothesized that, over time, brain activity would lateralize to the sensorimotor cortex contralateral to the imagined movement, with this effect observed for the neurofeedback group only. Further, we hypothesized that the actual task performance would improve in both groups as a function of time, with superior performance observed in the neurofeedback group.

Methods

Subjects

Eighteen right handed (Oldfield, 1971) subjects (8 male, 24.7 ± 3.8 years) agreed to participate in the study. All subjects were free of neurological disorder and each provided written, informed consent. Prior to the onset of the study, subjects were screened for compatibility with MEG (e.g., magnetic artifacts) according to institutional procedure. Subjects were randomly assigned to either the neurofeedback (FB) or control group based on the order of recruitment using a table generated prior to study onset. The study was conducted with approval from the Research Ethics Board at the IWK Health Centre.

Experimental task/paradigm

Regardless of group membership, subjects attended three experimental sessions performed at approximately the same time on consecutive days. A familiarization session immediately preceded the first experimental session during which subjects watched a gender-matched video describing the type of MI to be performed (i.e., kinesthetic, from the first-person perspective) and the task to be performed/imagined. The task used was a sequential button press paradigm performed with the non-dominant (left) hand. Briefly, a seven-digit sequence (4-2-3-1-3-4-2) was performed using a four-key response pad (Photon Control Inc. Burnaby, BC, Canada), with the numbers 1–4 representing the index, middle, ring and little finger respectively. The script accompanying the video emphasized the poly sensory aspects of MI, directing the subjects to attend to sensory information related to task performance (e.g., the feeling of the fingers moving up and down, and the clicking of buttons as they are pressed), which has been shown to facilitate MI performance (Braun et al., 2008). Following the video, participants observed the button sequence, completed the sequence with visual cues, and finally completed the sequence with no visual cues to establish equivalent task proficiency across participants.

All three experimental sessions for all participants included two ten-minute 'test' blocks and two ten-minute 'MI' blocks. Test blocks involved actual performance of the task, and MI blocks involved imagined performance of the task via MI. In all blocks, participants switched between rest and task/MI based on auditory cues provided in 10 s intervals (Fig. 1). Test blocks allowed for the assessment of task performance. During MI blocks, participants in the FB group received neurofeedback based on activity in bilateral sensorimotor cortices.

Neurofeedback enabled the FB group to 'see' the activity in their left and right sensorimotor cortices. Specifically, a bar graph showing side-by-side bars was presented to the FB participants on the projector screen. Following the auditory "Go" cue, real-time activation intensity

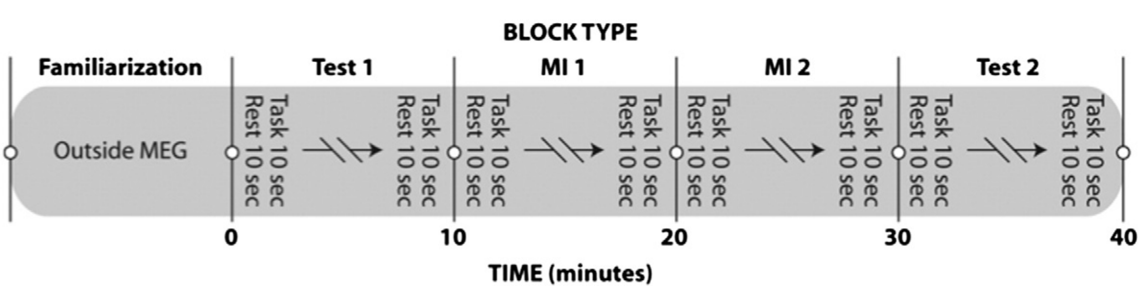

Fig. 1. Protocol timeline. Test and MI components were performed in 10-minute blocks, with participants switching between rest and task/MI based on auditory cues provided in 10 s intervals. A familiarization session occurred in the first study visit only.