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Motor imagery-based brain activity parallels that of motor execution: Evidence from magnetic source imaging of cortical oscillations

Sarah Kraeutner[a,b], *Alicia Gionfriddo*[a,c], *Timothy Bardouille*[c,d], *Shaun Boe*[a,b,c,*]

[a]*Laboratory for Brain Recovery and Function, Dalhousie University, Halifax, NS, Canada*
[b]*Department of Psychology and Neuroscience, Dalhousie University, Halifax, Nova Scotia, Canada*
[c]*School of Physiotherapy, Dalhousie University, Halifax, Nova Scotia, Canada*
[d]*Biomedical Translational Imaging Centre (BIOTIC), IWK Health Sciences Centre, Halifax, Nova Scotia, Canada*

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ABSTRACT

Motor imagery (MI) is a form of practice in which an individual mentally performs a motor task. Previous research suggests that skill acquisition via MI is facilitated by repetitive activation of brain regions in the sensorimotor network similar to that of motor execution, however this evidence is conflicting. Further, many studies do not control for overt muscle activity and thus the activation patterns reported for MI may be driven in part by actual movement. The purpose of the current research is to further establish MI as a secondary modality of skill acquisition by providing electrophysiological evidence of an overlap between brain areas recruited for motor execution and imagery. Non-disabled participants ($N=18$; 24.7 ± 3.8 years) performed both execution and imagery of a unilateral sequence button-press task. Magnetoencephalography (MEG) was utilized to capture neural activity, while electromyography used to rigorously monitor muscle activity. Event-related synchronization/desynchronization (ERS/ERD) analysis was conducted in the beta frequency band (15–30 Hz). Whole head dual-state beamformer analysis was applied to MEG data and 3D *t*-tests were conducted after Talairach normalization. Source-level analysis showed that MI has similar patterns of spatial activity as ME, including activation of contralateral primary motor and somatosensory cortices. However, this activation is significantly less intense during MI ($p<0.05$). As well, activation during ME was more lateralized (i.e., within the contralateral hemisphere). These results confirm that ME and MI have similar spatial activation patterns. Thus, the current research provides direct electrophysiological evidence to further establish MI as a secondary form of skill acquisition.

*Correspondence to: School of Physiotherapy, Dalhousie University, Rm 407, 4th Floor Forrest Building, 5869 University Avenue, PO Box 15000, Halifax, Nova Scotia, Canada, B3H 4R2. Fax: +1 902 494 1941.
E-mail address: s.boe@dal.ca (S. Boe).

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1. Introduction

Motor learning is the process of acquiring or strengthening a skill through repetitive practice and the provision of feedback (Newell, 1991). Motor learning occurs via plastic changes in the brain that are driven by this repetitive practice. While physical practice is recognized as the ideal vehicle to drive brain plasticity and thus motor learning, other forms of practice have been shown to facilitate skill acquisition. Motor imagery (MI) is a form of practice in which an individual mentally rehearses a motor task (Jeannerod, 1995, 2001). Motor imagery can take two forms, including first person or kinaesthetic imagery (i.e., imagining from "behind their own eyes" Munzert and Zentgraf, 2009), or third person visual imagery (i.e., imagining someone else performing the movement). Secondary to physical practice, MI has been used as a form of skill acquisition in numerous domains including surgery, sport, and music (Wulf et al., 2010; Moran et al., 2012). Motor imagery is suggested to facilitate skill acquisition in a manner similar to physical practice; that is plastic changes in the brain occur as a result of repetitive mental practice (Grezes and Decety, 2001; Miller et al., 2010; Schuster et al., 2011). The purported similarity in brain activity between MI and physical practice has led to an increased interest in the use of MI as an adjunct to physical practice in neurorehabilitation, particularly with regard to the treatment of upper limb impairment post-stroke (Sharma et al., 2009). If MI is to be used as an adjunct to physical practice to facilitate skill acquisition as outlined above, it is critical that similar brain regions are activated in both mental and physical practice.

At present, it remains unclear whether the neural correlates that underlie MI parallel those observed for physical practice (Grezes and Decety, 2001; Hétu et al., 2013), which we refer to throughout as motor execution (ME). In non-disabled individuals, the majority of neuroimaging studies have assessed task-related activation during MI using functional magnetic resonance imaging (fMRI) (Grezes and Decety, 2001; Hétu et al., 2013). Studies utilizing fMRI have largely determined that MI engages brain areas that overlap with ME, including the premotor (PMC), cingulate, and parietal cortices (Porro et al., 1996; Hanakawa et al., 2003; De Lange et al. 2008), however, this activation may be influenced by the type (kinaesthetic vs. visual) of MI employed (Guillot et al., 2009; Hétu et al., 2013). The primary motor cortex (referred to throughout as 'motor cortex') has also been proposed to play a critical role in MI, especially when employing kinaesthetic MI, though activation of the motor cortex during MI has not been consistently reported and thus has yet to be verified (De Lange et al., 2008; Hétu et al., 2013). In fact, a recent meta-analysis by Hétu et al. (2013) examining the brain regions that underlie MI concluded that while similar cortical areas were recruited across the studies, only 22 of 75 studies reported activation of the motor cortex. Furthermore, whether MI also recruits ventral and dorsal PMC (vPMC and dPMC, respectively), which are implicated in the preparation and guidance of movement (Rizzolatti et al., 1996; Binkofski et al., 2000), is conflicting in the literature (Lotze and Halsband, 2006; Munzert et al., 2009). Thus, due to the potential differences in areas recruited between ME and MI, MI is suggested to rely on a more widespread neural network in comparison with ME (Burianová et al., 2013).

Methodological approaches utilized in examining brain activity during MI may also contribute to variability in the results observed. In their meta-analysis, Hétu et al. (2013) reported that only two of 75 studies used electromyography (EMG) in addition to visual inspection to control for overt muscle activity. Thus, the resemblance in activation between MI and ME observed in many of these previous studies might be driven by brain activity associated with actual execution (i.e., cortical output to lower motor neurons). As such, it remains unclear whether 'pure' MI elicits the same spatial patterns as ME. Furthermore, the majority of studies examining brain activity underlying MI utilize either fMRI or positron emission tomography (PET) (Hétu et al., 2013), both of which rely on indirect measures of brain activity with low temporal resolution (Sutton et al., 2009; Cumming, 2014). Accordingly, these measures provide rich spatial information, but are limited in their ability to directly measure electrophysiological activity.

Unlike fMRI and PET, electroencephalography (EEG) provides a direct measure of brain activity with high temporal resolution (Niedermeyer, 1996). Analysis of EEG data during a sustained task (such as MI) can reveal changes in brain activity by assessing an increase or decrease in the magnitude of ongoing cortical oscillations, known as event-related synchronization and desynchronization (ERS/ERD) (Pfurtscheller and Lopes da Silva, 1999; Schoffelen and Gross, 2009). For example, EEG studies have shown that ERD occurs over contralateral sensorimotor areas in the beta frequency band (15–30 Hz) during MI and motor preparation and execution (Pfurtscheller and Neuper, 1997; Neuper et al., 2006; Formaggio et al., 2010). EEG is limited however in its ability to localize the underlying sources of beta ERD during MI and ME due mainly to spatial smearing of the electric potentials (Niedermeyer, 1996).

Similar to EEG, magnetoencephalography (MEG) obtains a direct measure of brain activity (Baillet et al., 2001). Unlike EEG however, MEG features considerably better spatial resolution (on the order of millimetres; Baillet et al., 2001) that provides the ability to more precisely identify source-level activity in the brain (Baillet et al., 2001; Schoffelen and Gross, 2009; Hari et al., 2010). For instance, Burianová et al. (2013) sought to identify the neural correlates of actual and imagined finger movements using both MEG and fMRI. In agreement with previous research, there was considerable overlap between the brain areas activated during MI and ME for both the MEG and fMRI data. Differences between MI and ME were noted however, with activity observed in brain areas crucial for visuospatial processing (e.g. left inferior parietal lobule, parahippocampus, right superior temporal gyrus and superior frontal gyrus) but not in areas related to somatosensory coordination during the MI condition. While this work capitalized on the ability of MEG to measure brain activity associated with MI with high temporal and spatial resolution, it is one of only a few studies to do so (Nakagawa et al., 2011; Di Rienzo et al., 2014). Moreover, this prior work examined brain activity associated with a simple motor task that was limited to flexion and extension movements of the fingers (Burianová et al., 2013). In light of the proposed use of MI to facilitate skill acquisition, ideally our understanding of how