



Multimodal functional imaging of motor imagery using a novel paradigm

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ABSTRACT

Neuroimaging studies have shown that the neural mechanisms of motor imagery (MI) overlap substantially with the mechanisms of motor execution (ME). Surprisingly, however, the role of several regions of the motor circuitry in MI remains controversial, a variability that may be due to differences in neuroimaging techniques, MI training, instruction types, or tasks used to evoke MI. The objectives of this study were twofold: (i) to design a novel task that reliably invokes MI, provides a reliable behavioral measure of MI performance, and is transferable across imaging modalities; and (ii) to measure the common and differential activations for MI and ME with functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG). We present a task in which it is difficult to give accurate responses without the use of either motor execution or motor imagery. The behavioral results demonstrate that participants performed similarly on the task when they imagined vs. executed movements and this performance did not change over time. The fMRI results show a spatial overlap of MI and ME in a number of motor and premotor areas, sensory cortices, cerebellum, inferior frontal gyrus, and ventrolateral thalamus. MI uniquely engaged bilateral occipital areas, left parahippocampus, and other temporal and frontal areas, whereas ME yielded unique activity in motor and sensory areas, cerebellum, precuneus, and putamen. The MEG results show a robust event-related beta band desynchronization in the proximity of primary motor and premotor cortices during both ME and MI. Together, these results further elucidate the neural circuitry of MI and show that our task robustly and reliably invokes motor imagery, and thus may prove useful for interrogating the functional status of the motor circuitry in patients with motor disorders.

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Introduction

Motor imagery (MI) is an internal rehearsal of simple or complex motor movements without overt physical action (Annett, 1995; Jeannerod, 1995; Porro et al., 1996). Although difficult to describe verbally, MI involves kinesthetic and visual imagery and is characterized by vivid mental representations of movement execution from a first-person perspective (Munzert et al., 2009; Porro et al., 1996). Motor imagery plays a critical role in motor skill learning and sports training (Brouziyne and Molinaro, 2005; Murphy, 1994), as well as in prosthesis control (Hochberg et al., 2006) and motor rehabilitation in patients with motor disorders (Dijkerman et al., 2004; Kimberley et al., 2006; Sharma et al., 2006). Such ample clinical and neurophysiological applications of MI emphasize the necessity for deeper understanding of the neural mechanisms engaged in motor imagery.

The last two decades have yielded a number of imaging studies investigating the neural correlates of motor execution (ME) and MI, as well as their functional overlap, using various techniques, such as

positron emission tomography (PET; e.g., Decety et al., 1994; Naito et al., 2002; Roland et al., 1980; Stephan et al., 1995), electroencephalography (EEG; e.g., Beisteiner et al., 1995; Rodriguez et al., 2004; Thayer and Johnson, 2006), functional magnetic resonance imaging (fMRI; e.g., Lotze et al., 1999; Porro et al., 1996; Roth et al., 1996), and magnetoencephalography (MEG; e.g., Lang et al., 1996; Nagakawa et al., 2011; Schnitzler et al., 1997). Convergent evidence shows that during ME the motor and premotor cortices, i.e., the primary motor cortex (M1), supplementary motor area (SMA), pre-supplementary motor area (pre-SMA), and ventral and dorsal premotor cortices (vPMC and dPMC, respectively) are modulated by the cerebello-thalamo-cortical loop. Other essential ME areas include the basal ganglia, primary somatosensory cortex (S1), and posterior parietal cortex—specifically, the superior and inferior parietal lobules (SPL and IPL, respectively).

Some studies report that the neural correlates of MI substantially overlap with those subserving ME (Jeannerod, 2001; Lotze and Halsband, 2006), especially within the neural circuits involved in the early stages of motor control (i.e., motor planning). These circuits include the supplementary motor area, premotor areas, and posterior parietal cortex. In light of these findings, Jeannerod (2001) proposed that ME and MI are functionally equivalent in that the neural processes are shared but in MI overt production of movement is inhibited. However,

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a substantial number of studies have reported contradictory results. For instance, while several studies show consistent and even somatotopic activations of the primary motor cortex (Porro et al., 1996; Stippich et al., 2002), others fail to show any involvement of M1 in motor imagery (Roland et al., 1980; Stephan et al., 1995). Lotze and Halsband (2006) and Sharma et al. (2006) argue that the involvement of M1 during motor imagery is dependent on the intensity and the complexity of the imagined movement and emphasize the importance of task selection, training, and imaging techniques. Similarly, studies differ with respect to activation of SMA during motor imagery. Although it is generally found that pre-SMA is active during movement selection and preparation (Gerardin et al., 2000; Lotze et al., 1999; Roland et al., 1980), conflicting results pertain to the role of posterior SMA. On the one hand, posterior SMA has been found active during ME (Deiber et al., 1991; Stephan et al., 1995), but on the other hand, several authors claim that posterior SMA may be central to the inhibition of overt movement in MI (Kasess et al., 2008; Solodkin et al., 2004). Research findings also diverge in the degree of vPMC and dPMC activations during motor imagery (Lotze and Halsband, 2006; Munzert et al., 2009). vPMC is argued to be critical for action execution, action observation (Rizzolatti et al., 1996), and sensory guidance of movement, whereas dPMC is proposed to be essential in learning of associations between sensory stimuli and specific movements; thus utilizing somatosensory strategies (Binkofski et al., 2000; Vry et al., 2012). Finally, some researchers have argued that motor imagery is supported by a distributed neural system that relies more on sensory planning and preparation (i.e., activity in parietal and temporal areas) than executive motor processes (i.e., activity in primary motor cortices; Annett, 1995).

There is a number of potential explanations for these disparate results; for instance the diverse variety of brain mapping techniques, mental training procedures, instructions, analysis tools, tasks that have been employed to invoke MI, as well as inadequate behavioral monitoring (Gao et al., 2011; Munzert et al., 2009; Oosterhof et al., 2012; Porro et al., 1996). Motor imagery is exclusively an internal process and therefore is fundamentally difficult to control and monitor. Ideally, empirical paradigms should provide some measure of imagery success, maximizing the consistency and continuity of imagery engagement and vividness. However, studies differ substantially in the tasks used to invoke MI, pre-experimental training, movement monitoring, and reported imagery strategies. The classical paradigms for MI involve simple hand and finger movements, e.g., hand/finger flexion (Gerardin et al., 2000; Lotze et al., 1999); button pressing (Guillot et al., 2009; Kasess et al., 2008); finger-to-thumb opposition (Porro et al., 1996; Roland et al., 1980; Solodkin et al., 2004), joystick movement (Deiber et al., 1991; Stephan et al., 1995); or target tracing (Binkofski et al., 2000). These tasks are problematic for two main reasons. Firstly, because of their simple, repetitive, and predictable nature, they may result in the fluctuation of attention and vigilance levels during long testing blocks (e.g., Porro et al., 1996). Secondly, most do not include any behavioral measure of MI performance (Lotze and Halsband, 2006) and are thus unable to independently confirm that participants actually engage in MI as instructed. Confirmation of MI often relies on rather indirect measures, e.g., physiological indices of heart and respiratory rates, which have been proposed to increase during MI (Decety et al., 1991); or duration of MI, which is argued to positively correlate with duration of ME (Decety and Michel, 1989).

More recently, Hanakawa et al. (2003, 2008) aimed to rectify some of the early methodological limitations, introducing an external behavioral measure in a sequential movement and imagery (SMI) task. In the SMI task, participants learn a simple sequential tapping sequence and are cued to the first finger of the tapping sequence, as well as to the number of taps to be executed or imagined. The critical point of the behavioral response is at the end of the task period when a question mark appears and the participants are asked to report the next finger in the tapping sequence. Albeit an elegant design, a few methodological issues are evident, for instance the visual presentation of the stimuli, verbal

report of the target response, or presenting experimental conditions in separate imaging runs. The purpose of the current study was to design and test a novel MI paradigm, which has (i) a behavioral outcome measure that directly and objectively indexes success in the imagery task, (ii) an unpredictable auditory cueing sequence that promotes sustained imagery vigilance, (iii) a randomized order of all experimental conditions within each testing run, conducive to a direct comparison of experimental conditions in the analysis, and, (iv) which is suitable, in its exact experimental layout, for testing with various imaging modalities, such as fMRI, EEG, or MEG. We report the neural activity associated with task performance in a group of participants measured using fMRI. To demonstrate the cross-modal applicability of the paradigm, we also report brain responses from a complementary imaging technique, magnetoencephalography (MEG). The easy transferability of the paradigm across testing modalities has clinical and empirical benefits. For instance, clinically the EEG or MEG environment may be more suitable than fMRI to claustrophobic individuals, children, or noise-sensitive individuals. Empirically, the spatial resolution of fMRI is superior to that of MEG, whereas the temporal resolution of MEG is near perfect, superior to that of fMRI. Thus, the results of our study converge complementary spatio-temporal information relevant to motor execution and motor imagery.

Methods

Participants

Fourteen young adults (age range = 18–31; mean age = 25 years; SD = 4.2; 7 females) participated in the study. All participants were strongly right-handed (Oldfield, 1971), had normal or corrected-to-normal vision, and had no history of neurological impairment or psychiatric illness. All participants provided written informed consent approved by the Macquarie University Human Research Ethics Committee.

Task

Participants were required to perform the following conditions: execution of specific finger movements with the right or left hand, imagination of specific finger movements with the right or left hand, and rest (see Fig. 1).

Motor execution

The fingers of each hand were assigned numbers (1 = thumb, 2 = index finger, 3 = middle finger, 4 = ring finger, 5 = little finger). Starting from a default position (i.e., resting their arms alongside the body, with the ventral surface against the plinth, to minimize elbow flexions during the task, and keeping their arms and hands completely relaxed, with their fingers extended but relaxed), participants were presented with a random sequence of 4 or 5 spoken digits and were asked to either slowly curl in the respective finger or extend it again to the default position if the same digit occurred again. At the end of each cue sequence, participants saw a picture of a hand and were asked to decide whether their final finger configuration was the same or different from that of the displayed hand. They indicated “yes” by slightly moving the toes of their right foot or “no” with the toes of their left foot. An examiner outside the testing room manually recorded the responses. We chose a toe response to minimize interference with both the behavioral and neural aspects of the finger-moving task.

Motor imagery

In the MI condition, participants performed the same task but instead of actually moving their fingers they were asked to imagine performing the movements. Participants were trained prior to the study on motor imagery (see the Training section below) and were explicitly and repeatedly instructed to maintain the vividness of motor

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