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MOTOR EXECUTION AND MOTOR IMAGERY: A COMPARISON OF FUNCTIONAL CONNECTIVITY PATTERNS BASED ON GRAPH THEORY

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Abstract—Motor execution and imagery (ME and MI), as the basic abilities of human beings, have been considered to be effective strategies in motor skill learning and motor abilities rehabilitation. Neuroimaging studies have revealed several critical regions from functional activation for ME as well as MI. Recently, investigations have probed into functional connectivity of ME; however, few explorations compared the functional connectivity between the two tasks. With betweenness centrality (BC) of graph theory, we explored and compared the functional connectivity between two finger tapping tasks of ME and MI. Our results showed that using BC, the key node for the ME task mainly focused on the supplementary motor area, while the key node for the MI task mainly located in the right premotor area. These results characterized the connectivity patterns of ME and MI and may provide new insights into the neural mechanism underlying motor execution and imagination of movements.

Key words: motor execution, motor imagery, functional connectivity, betweenness centrality, key nodes.

INTRODUCTION

Motor imagery (MI) is one of the remarkable abilities of the mind. It refers to the mental representation of an overt action without any concomitant motor execution (ME) (Jeannerod, 1994). ME and MI, as indispensable parts of our daily life, both have been extensively explored from different aspects in the neuroscience communities.

At the behavioral level, numerous reports have suggested that both ME and MI are effective in motor skill learning and motor abilities rehabilitation (Page et al., 2001; Sharma et al., 2006; Olsson et al., 2008). Moreover, evidence supports that ME and MI involve in similar cognitive processes because of the parallel durations between the real execution and mental representation of overt actions such as walking or writing (Decety and Jeannerod, 1995; Papaxanthis et al., 2002).

Furthermore, neuroimaging studies at the activation level widely investigate ME and MI to identify the pivotal brain regions involved in tasks by using neuroimaging techniques, such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET). Explorations indicated that ME and MI share overlapping activated pattern in some critical regions including the supplementary motor area (SMA), premotor area (PMA), primary sensorimotor area (M1/S1), posterior parietal lobe (PPL), striatum, cerebellum and thalamus, in spite of their different volume and intensity of activation (Lotze et al., 1999; Gerardin et al., 2000; Lacourse et al., 2005; Munzert et al., 2009; Zhang et al., 2011). Moreover, these activated brain regions have been suggested to be functional interacted with each other in tasks (Liu et al., 1999; Büchel and Friston, 2000). Therefore the characteristics of functional interaction between activated brain regions could be further investigated using functional connectivity analysis.

Functional connectivity in brain regions of motor network can appear as homunculus organization. Studies on the basis of the knowledge of homunculus organization in the primary motor area and cerebellum suggested that functional subregions of the motor network are one-on-one linked to their functional homolog in the contralateral hemisphere and organized in a somatotopic fashion, and high demanding tasks may engage prefrontal and parietal cortices along with cerebellar lobules VI and VII (van den Heuvel et al., 2010b; Stoodley et al., 2012). The analysis of

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Abbreviations: BC, betweenness centrality; E_{bc}, edge betweenness centrality; fMRI, functional magnetic resonance imaging; lCere, left cerebellum; lM1/S1, left primary sensorimotor area; lPMA, left premotor area; lPPL, left posterior parietal lobe; lStria, left striatum; lThal, left thalamus; M1/S1, primary sensorimotor area; ME, motor execution; MI, motor imagery; N_{bc}, node betweenness centrality; PMA, premotor area; PPL, posterior parietal lobe; ROI, region of interest; rCere, right cerebellum; rM1/S1, right primary sensorimotor area; rPMA, right premotor area; rPPL, right posterior parietal lobe; rStria, right striatum; rThal, right thalamus; SMA, supplementary motor area.

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functional connectivity in motor networks for motor tasks could be explored from different perspectives. Sun et al. (2007) revealed that with coherence analysis, brain regions showing significant coherence with the left M1/S1 were located in the PMA, SMA and cingulate motor area for a bimanual motor sequence task. Kincses et al. (2008) reported that with independent component analysis, the fronto-parieto-cerebellar network and posterior parietal-premotor network were identified as two task-related components in a sequential moving task. Jiang et al. (2004) found that with graph theory analysis, the connectivity degree of several brain regions in the motor function network such as the left M1, left PMA and left cerebellum increased from the resting state to the finger tapping task state, while the left basal ganglia and the right cuneus decreased. So far, related studies of functional connectivity about motor tasks have been reported only for the ME tasks, few studies have focused on MI tasks.

In the aforementioned researches of functional connectivity on ME tasks, several techniques have been used, such as correlation/coherence analysis, independent component analysis, graph theory and so on (Jiang et al., 2004; Sun et al., 2007; Kincses et al., 2008; Uddin et al., 2008). Among these methods, graph theory has been introduced to the neuroimaging research communities recently and has received increasing attention in functional connectivity analysis (Bullmore and Sporns, 2009; Rubinov and Sporns, 2010). It can describe the brain's connectivity patterns based on complex brain network analysis. A brain network is constructed by a number of nodes and a set of edges, where the nodes can represent brain regions of interest and the edges can denote the connections between pairs of nodes. The characteristics of each node/edge can be revealed by different metrics of the brain network analysis. One metric named betweenness centrality (BC), which is based on the idea that central nodes/edges participate in many short paths within a network, can examine the global role of nodes/edges and identify key nodes/edges in controlling the information flow of the brain network (Freeman, 1979; He et al., 2009; Rubinov and Sporns, 2010).

The present study examined and compared the connectivity patterns of critical brain regions in ME and MI sequential finger tapping tasks. Specifically, we stressed the global role of nodes/edges based on several critical brain regions for ME and MI with BC and identified several key nodes and key edges for ME and MI tasks respectively (the reasons why we selected BC in this study is discussed in detail in Appendix A). Our results potentially provided novel insights into the neural mechanism underlying ME and MI.

EXPERIMENTAL PROCEDURES

Participants

Twenty-six right hand-dominant subjects (12 males and 14 females, mean (SD) age = 23 (2) years) were recruited in our experiment. Participants with histories of neurological disorders, psychiatric disorders, experience with typewriters, or any experience learning to play musical instruments were excluded. All participants passed Edinburgh Handedness Inventory, Movement Imagery Questionnaire (Hall and Martin, 1997) and Vividness of Movement Imagery Questionnaires (Isaac et al., 1986). According to these questionnaires, we requested the participants to understand what kinesthetic imagery is, and to employ this imagery strategy during the whole experimental procedure. Moreover, all participants provided written consent according to the guidelines set by the MRI Center of Beijing Normal University.

Experimental design and procedures

The present study was extended from our previous study (Zhang et al., 2011). The procedure of the experiment mainly included familiar exercises, an ME task and an MI task, which has been reported as a part of the whole experimental procedure in our previous study (Zhang et al., 2011).

Outside the scanner, all the participants were first instructed that from their index to little finger, each of the four fingers of their right hand represented a single digit number: one, two, three, and four. Next, they were instructed to tap their right index finger with a metronome at 4 Hz to learn the rhythm required in the following scan session, after which they tapped 1–2–3–4 at 4 Hz for 30-s epoch. Then, they tapped the set sequence 4–2–3–1–3–4–2 at 4 Hz for 30-s epoch, and imagined tapping the set sequence at 4 Hz for 30-s epoch. This familiarization exercise was necessary for preventing confusion in each scan session and still preserved the novelty of the tasks. After finishing these exercises, the participants were prepared for the ME/MI tasks in the scanner.

Two scanning sessions, ME and MI tasks, were completed in the scanner. The two 4.5-min sessions were separated by a 5-min inter-session rest period. Each task session consisted of four 30-s epochs of executing/imagining the motor sequence, interspersed with five 30-s rest blocks. The assignment of scan orders was counterbalanced across subjects. In each scanning session, a sequential finger movement task was adopted, and the press sequence was 4–2–3–1–3–4–2. Subjects attempted to execute or imagine the set sequence with their right hand fingers at a self-paced rate according to the 4-Hz rate which they had learned in the familiar exercises when PUSH was displayed on the screen, and then relaxed when REST was displayed on the screen. The task instruction was given to each participant before the scanning as ''You will attend two sessions of tasks including ME and MI. The type of the task will be displayed on the screen before the task starting. If the task is ME, you need to tap 4–2–3–1–3–4–2 with your right hand fingers as fast as the rate which you have just learned outside the scanner, and if the task is MI, you need to imagine tapping 4–2–3–1–3–4–2 with your right hand fingers as fast as the pace which you have just learned outside the scanner.'' The descriptions of the task type, which were displayed to the subject via a mirror mounted on the head coil, were presented