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Effector-independent brain activity during motor imagery of the upper and lower limbs: An fMRI study

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HIGHLIGHTS

- Brain activity was measured by functional magnetic resonance imaging.
- We evaluated the common brain region of motor imagery of the right/left hands or feet.
- The left supplemental motor area and inferior frontal gyrus were commonly activated.

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ABSTRACT

We utilized functional magnetic resonance imaging (fMRI) to evaluate the common brain region of motor imagery for the right and left upper and lower limbs. The subjects were instructed to repeatedly imagined extension and flexion of the right or left hands/ankles. Brain regions, which included the supplemental motor area (SMA), premotor cortex and parietal cortex, were activated during motor imagery. Conjunction analysis revealed that the left SMA and inferior frontal gyrus (IFG)/ventral premotor cortex (vPM) were commonly activated with motor imagery of the right hand, left hand, right foot, and left foot. This result suggests that these brain regions are activated during motor imagery in an effector independent manner.

1. Introduction

Motor imagery is a mental process that involves the simulation of motor execution [25]. Many studies have reported significant effects of motor imagery practice on improvement of motor skill, muscle strength and joint flexibility [11,17,31,34,47]. In addition, motor imagery has been utilized to create a brain computer interface [37]. Neuroimaging studies using functional magnetic resonance imaging (fMRI) have demonstrated that various regions such as the supplemental motor area (SMA), the premotor cortex (PM), the parietal region, the basal ganglia and the cerebellum are activated during motor imagery [7,8,16,19,20,29,30,32,33,36]. Previous studies also report that brain activity during motor imagery largely overlaps activity that occurs during actual motor execution [16,19,20,30,31]. A previous study suggested that a hierarchy exists in the action representation (i.e. effector dependent and effector independent manner) [23]. We consider that clarifying effector-independent activity during motor imagery would give important information to understand the neural mechanisms underlying higher order action representation in motor imagery.

Several studies have found activation of the left inferior frontal gyrus (IFG)/ventral PM (vPM) during voluntary hand movements. This activation is independent of hand side [41]. For example, Heim et al. report that the left IFG and SMA were commonly activated not only during right and left hand movements, but also during speech [21]. In addition, patients with a stroke in the left hemisphere exhibited impaired voluntary movements of both right and left hands [18]. Therefore, motor-related brain regions in the left hemisphere would have an important role in motor execution irrespective of the side of the activated hand. Activity in the left PM was also observed during action planning and motor imagery [1,2]. For example, the left frontal operculum (Brodmann area: BA 44) and the SMA were activated during imagery involving both right and left hand unimanual movements [1].

The left PM is also activated during voluntary foot movements [5]. A previous study reported that the left vPM was activated during imagery of the right lower limb movement [45]. A recent meta-analysis demonstrated that brain activity during upper and

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lower limb movement was observed in the front-parietal regions including the left IFG [22]. However, since this meta-analysis did not address the independence of the right and left limbs, it remains unclear as to whether the left IFG was commonly activated during motor imagery of right and left foot movement. Swinnen and colleagues demonstrated that the left IFG/vPM and parietal regions are activated during both right and left hand-foot coordination movements. This suggests that the left parietal-premotor areas are candidates for effector-independent movement encoding as the highest level in the action representation hierarchy [43]. The overall conclusion gleaned from the above studies is that the left IFG/vPM plays an important role in both motor execution and imagery, irrespective of hand or foot side. This leads to the supposition that the left IFG/vPM is a viable candidate for the structure encoding motor imagery in an effector-independent manner, since the loci of increased brain activity during motor execution and motor imagery are similar [10]. To date, no studies have examined whether the left IFG/vPM is commonly activated during motor imagery of the right/left hands or feet.

To evaluate the above hypothesis, the present study utilized fMRI, and measured the blood oxygenation level-dependent (BOLD) signal to evaluate the common brain regions activated by motor imagery of the right and left as well as the upper and lower limbs. A previous study demonstrated that the modality of explicit imagery (i.e. kinesthetic and visual imagery) affects brain activity [16]. In the present study, we investigated brain activity during kinesthetic motor imagery. We hypothesized that activity in the left IFG/vPM would be commonly observed among the four imagery conditions (i.e. right hand, left hand, right foot, and left foot).

2. Methods and materials

2.1. Subjects

Seventeen normal subjects (one female and 16 males; mean age 23.3 ± 2.5 years) participated in this study. All subjects were undergraduate or graduate students. All of them were right-handed according to the Edinburgh Inventory [38], and right-footed according to Chapman's Footedness Test [6]. The subjects had no history of neurological or psychiatric disorders. Before the experiment, written informed consent was obtained from all subjects. The study was approved by the Human Research Ethics committee of the Faculty of Sport Sciences, Waseda University.

2.2. Procedure

The subjects performed four motor imagery tasks: (1) right hand imagery (RH), (2) left hand imagery (LH), (3) right foot imagery (RF) and (4) left foot imagery (LF). In the RH and LH tasks, the subjects were asked to repeatedly imagine extension and flexion of the right or left hand. In the RF and LF tasks, the subjects were instructed to repeatedly imagine plantar flexion and dorsiflexion of the right or left ankle. Before the fMRI scan, differences in motor imagery between kinesthetic and visual imagery were explained to the subjects. The subjects were instructed to perform the imaging of the movements with a comfortable, self-paced rhythm utilizing kinesthetic imagery and to keep the same rhythm among the four conditions. A practice session with several trials of motor imagery including extension and flexion was performed before the recording to enable the subjects to become familiar with the situation. After recording each condition, we verbally asked the subjects whether motor imagery with the same rhythm could be successfully performed. It was confirmed that all subjects performed clear motor imagery in all conditions.

For the MRI scans, a 5 min 12 s run for each condition consisted of five alternate repetitions of the task and a rest period. The durations of the task and the rest periods were both 30 s. The first four volumes (12 s) of each fMRI session were discarded because of unstable magnetization. The subjects were presented with a blue-filled or red-filled circle cue via a PC controlled projector system (VisuaStimDigital, Resonance Technology Co., USA). The circles were presented with a black background and were viewed through non-magnetic goggles. When the blue cue was presented, the subjects were instructed to mentally reproduce the requested limb movement without any muscle activation. When the red cue was shown, the subjects were asked to relax and to not image. The subjects were also asked to keep their muscles relaxed and not to think about anything throughout the entire procedure. Any communication between the experimenter and the subject was made via intercom.

2.3. fMRI data acquisition and analysis

All images were acquired using a 1.5 T MR scanner (Signa, General Electric, Wisc., USA). BOLD contrast functional images were acquired using T2*-weighted echo planar imaging (EPI) free induction decay (FID) sequences with the following parameters: TR 3000 ms, TE 50 ms, FOV 22 cm × 22 cm, flip angle 90°, slice thickness 5 mm and gap 1 mm. The orientation of the axial slices was parallel to the AC–PC line. For anatomical reference, T1-weighted images (TR 30 ms, TE 6 ms, FOV 24 cm × 24 cm, flip angle 90°, slice thickness 1 mm and no gap) were also obtained for each subject.

The raw data were analyzed with a Statistical Parametric Mapping (SPM8, Wellcome Department of Cognitive Neurology, London, UK) [12–14] program implemented in MATLAB (Mathworks, Sherborn, Massachusetts, USA). Realigned images were normalized to the standard space of the Montreal Neurological Institute brain (MNI brain). Subsequently, smoothing was executed with an isotropic three-dimensional Gaussian filter with full-width at a half-maximum (FWHM) of 8 mm. High-pass filters (128 s) were also applied and low frequency noise and global changes in the signals were removed.

Statistical analysis was performed on two levels. The first-level analysis performed for each subject was done with the general linear model. We constructed a statistical parametric map of the t-statistic for each of the four contrasts; (1) RH, (2) LH, (3) RF, and (4) LF. Subject-specific contrast images of the estimated parameter were used for the second-level analysis (random-effect model) [15]. The second-level analysis utilizing a full factorial design (one-way ANOVA, factor = limb, four levels) was performed to extend the inference of individual activation data to the general population. A conjunction analysis was also employed in order to detect brain regions activated commonly in all four conditions utilizing SPM8 [39]. Anatomical locations and Brodmann's areas were determined utilizing the anatomy tool box (version 1.8) of SPM. The statistical threshold was set at $p < 0.001$ uncorrected (spatial extent > 10 voxels) [24]. If significant activation was evaluated as 'Not found in any probability map', it was excluded from description in the results section as well as in the tables.

3. Results

Brain activities related to RH imaging were located in the left SMA (BA 6), rolandic operculum (BA 44), and primary somatosensory cortex (S1) (BA 1). In the right hemisphere, activation was observed in the PM (BA 6) (Fig. 1, Table 1). Regions activated by LH imaging were located in the left SMA (BA 6), PM (BA 6), IFG (BA 44), pallidum, amygdala, caudate nucleus, and cerebellum. The activities in the right hemisphere were seen in the PM (BA 6), rolandic