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MOTOR IMAGERY BEYOND THE MOTOR REPERTOIRE: ACTIVITY IN THE PRIMARY VISUAL CORTEX DURING KINESTHETIC MOTOR IMAGERY OF DIFFICULT WHOLE BODY MOVEMENTS

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Abstract—To elucidate the neural substrate associated with capabilities for kinesthetic motor imagery of difficult whole-body movements, we measured brain activity during a trial involving both kinesthetic motor imagery and action observation as well as during a trial with action observation alone. Brain activity was assessed with functional magnetic resonance imaging (fMRI). Nineteen participants imagined three types of whole-body movements with the horizontal bar: the giant swing, kip, and chin-up during action observation. No participant had previously tried to perform the giant swing. The vividness of kinesthetic motor imagery as assessed by questionnaire was highest for the chin-up, less for the kip and lowest for the giant swing. Activity in the primary visual cortex (V1) during kinesthetic motor imagery with action observation minus that during action observation alone was significantly greater in the giant swing condition than in the chin-up condition within participants. Across participants, V1 activity of kinesthetic motor imagery of the kip during action observation minus that during action observation alone was negatively correlated with vividness of the kip imagery. These results suggest that activity in V1 is dependent upon the capability of kinesthetic motor imagery for difficult whole-body movements. Since V1 activity is likely related to the creation of a visual image, we speculate that visual motor imagery is recruited unintentionally for the less vivid kinesthetic motor imagery of difficult whole-body movements. © 2015 The Authors. Published by Elsevier Ltd. on behalf of IBRO. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Key words: Brodmann's area 17, visual imagery, FMRI, action observation.

INTRODUCTION

Motor imagery is defined as the mental execution of an action without any overt movement or muscle activation (Jeannerod, 2001). Motor imagery training has been shown to be effective for improving motor skills (Feltz and Landers, 1983; Pascual-Leone et al., 1995; Allami et al., 2008), and is widely used in sports as well as for the recovery of function following motor impairment (Lotze and Halsband, 2006; Mizuguchi et al., 2012). Since the effect of motor imagery training is dependent upon a person's capability for motor imagery (Isaac, 1992; Mulder et al., 2004), evaluation of motor imagery capability is an important aspect in the prediction of the efficacy of training effects.

It has been suggested that the capability of motor imagery of hand movement is associated with the intensity of activity in the premotor cortex (PM) (Guillot et al., 2008). Studies using transcranial magnetic stimulation (TMS) also support this finding: Enhancement of corticospinal excitability is correlated with the vividness of motor imagery of hand movements (Lebon et al., 2012; Williams et al., 2012). Previous studies suggest that brain activity during motor imagery of difficult, complex whole-body movements is different from that of hand movements (Szameitat et al., 2007; Olsson et al., 2008; Wei and Luo, 2010). For example, the supplementary motor area (SMA) was activated during motor imagery of hand movements (Kuhtz-Buschbeck et al., 2003; Lacourse et al., 2005), and was not activated during motor imagery of a high jump in novices (Olsson et al., 2008). Also, while many TMS studies have demonstrated that the amplitude of motor-evoked potentials increase during motor imagery of hand movements (Fadiga et al., 1999; Mizuguchi et al., 2009, 2013a,b), this increase has not been observed during motor imagery of complex whole-body movements such as tennis in novices (Fourkas et al., 2008). Thus, if a person lacks a motor representation for a difficult whole-body movement, he/she would not be able to recruit motor-related regions during motor imagery.

Motor imagery can be divided into two categories: kinesthetic motor imagery and visual motor imagery (Roberts et al., 2008; Guillot et al., 2009). A previous study suggested that visual motor imagery was easier to create than kinesthetic motor imagery (Guillot et al., 2004). Interestingly, visual areas were activated during motor imagery of a high jump in novices even when they were asked to "feel" the high jump rather than "see" it

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Abbreviations: BA, Brodmann's area; BCI, brain computer interface; BOLD, blood oxygenation level dependent; fMRI, functional magnetic resonance imaging; IPL, inferior parietal lobule; PM, premotor cortex; SMA, supplemental motor area; SPL, superior parietal lobule; TMS, transcranial magnetic stimulation; V5, visual area 5; VMIQ, Vividness of Movement Imagery Questionnaire.

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(Olsson et al., 2008). Based on this result, we hypothesize that visual motor imagery is recruited unintentionally during awkward types of kinesthetic motor imagery. To test this hypothesis, we analyzed brain activity during kinesthetic motor imagery of difficult whole-body movements and focused our analysis on brain areas known to be activated during visual motor imagery. We also evaluated how the observed activity was related to the participants' overall capability for kinesthetic motor imagery. We used the giant swing, the kip and the chin-up. The giant swing represented a novel, particularly difficult whole-body movement that none of the participants had attempted to perform.

EXPERIMENTAL PROCEDURES

Participants

Nineteen male participants (age: range 21–33 years old, mean 24.3 ± 3.6 years old) participated in this study. Seventeen of the participants were right-handed according to the Edinburgh Inventory (Oldfield, 1971). All participants had normal or corrected normal vision. All participants received a detailed explanation of the experimental procedures before the experiment, and written informed consent was obtained from all participants. The study was approved by the Human Research Ethics committee of Waseda University.

Procedure

We used three types of whole-body movement which all involved the use of a horizontal bar: (1) the giant swing, (2) the kip, and (3) the chin-up (Fig. 1A). No participant had ever tried to perform the giant swing (most difficult, and essentially an impossible movement for the participants). All participants were able to perform the chin-up (the easiest movement of the three). Eight of the participants were able to perform the kip. The experience involving the movements was confirmed verbally after the experiment. In the motor imagery condition, to control the number of trials in the task and to minimize the differences in the imaging of the same movements across participants, the participants observed a movie via a projector system with non-magnetic goggles (VisuaStimDigital, Resonance Technology Co, USA) during motor imagery. The participants were asked to imagine movements at the same pace as the presented movements. Thus, brain activity in the motor imagery conditions included activity related to both motor imagery and action observation. To subtract brain activity of action observation from the motor imagery condition, the participants also conducted an action observation condition. Thus, the participants performed under two conditions separately. In total, then, the participants completed six different conditions. In the action observation condition, the participants were asked to only observe the presented movements, and to not imagine any movement. Before performing the functional magnetic resonance imaging (fMRI) scan, the difference between kinesthetic motor imagery and visual motor imagery (Roberts et al., 2008) was explained to the participants. They were subsequently instructed to imagine the presented movements using kinesthetic motor imagery at the actor's pace and to not use visual motor imagery in the motor imagery conditions. The participants were asked to maintain their gaze at the center of the projection and to not alter it. The participants were also asked to keep their muscles relaxed and to not think about anything throughout the entire procedure. After each motor imagery condition, we asked participants whether kinesthetic motor imagery was used appropriately.

fMRI data acquisition and analysis

All images were acquired using a 1.5 T MR scanner with an 8-channel head coil (Signa, General Electric, WI, USA). Blood oxygenation level-dependent (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.

Four sessions of motor imagery with action observation (motor imagery condition) and four sessions of action observation condition were completed. For the MRI scan, a session consisted of nine alternate repetitions of the task (3 types of movement × 3 repetitions) and rest periods. The order of the three movements was randomized. The task and rest period durations were both 30 s. A giant swing took 1.9 s, so 16 giant swings were observed per period. A kip took 6 s, so 5 kips were observed per period. A chin-up took 2.5 s, so 12 chin-ups were observed per period. In the rest period, a static picture of the actor hanging on the horizontal bar was observed. One session took 9 min 12 s. The first four volumes (12 s) of each fMRI session were discarded because of unstable magnetization. The order of sessions was randomized across participants. The duration of the inter-session interval was determined by each participant in order to ensure that they were neither fatigued nor sleepy. The duration of the inter-session interval was usually less than 5 min. The entire experiment always took less than 2 h.

The raw data were analyzed utilizing Statistical Parametric Mapping (SPM8, Wellcome Department of Cognitive Neurology, London, UK) (Friston et al., 1994, 1995a,b) implemented in MATLAB (Mathworks, Sherborn, MA, USA). Realigned images were normalized to the standard space of the Montreal Neurological Institute brain (MNI brain). Smoothing was executed with an isotropic three-dimensional Gaussian filter with full-width at 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. A first-level analysis was performed for each subject using a general linear model. We constructed a statistical parametric map of the *t*-statistic for the six simple contrasts, (1) motor imagery of giant swing vs. rest, (2) motor imagery of kip vs. rest, (3) motor imagery of chin-up vs. rest, (4) action observation of giant swing