Motor imagery while judging object–hand interactions

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Received 20 May 2005; accepted 24 May 2005

Because corticospinal excitability, as assessed with transcranial magnetic stimulation, has been repeatedly shown to increase during motor imagery, we used this approach to determine whether appreciating object–hand interactions involves motor imagery. Corticospinal excitability was measured in nine healthy participants who were asked to decide whether a hand presented in a given posture was compatible with the use of an object. The control task consisted in deciding whether two hands were in the same posture; a dimming task was used to determine the baseline. We found a significant increase in corticospinal excitability while judging object–hand interactions in comparison with the two other tasks. This finding suggests that predicting the consequences of an action involves implicit motor imagery. *NeuroReport* 16:1193–1196 © 2005 Lippincott Williams & Wilkins.

Key words: Corticospinal excitability; grasping; motor imagery

INTRODUCTION

Motor imagery probably involves the same motor representations as those activated while planning and executing overt movements [1]. Indeed, when participants imagine themselves performing a movement, a strong correlation is observed between the time course of the imagined and actual movements [2]. Similarly, the physiological parameters reflecting exercise adaptation evolved in the same way in both conditions [3], and functional imaging studies have repeatedly shown that brain regions activated during movement execution are also active during the motor imagery of the same action [4]. Altogether, these studies have contributed to determine the nature and anatomical substrate of motor representations. However, little is known about the processes that contribute to predict the consequences of an action and, in particular, whether they implicitly require motor imagery. Johnson [5] has provided evidence that assessing object–hand interactions involves precise movement simulation. Indeed, the time required to make a judgement about object–hand interactions was a function of the biomechanical limits that constrained the real movements. This suggests that evaluating the consequences of an action may involve the activation of analogue motor representations and possibly the building of a motor plan. In accordance with this view, Buxbaum *et al.* [6] reported that patients with ideomotor apraxia, a deficit in motor planning, have great difficulties in judging object–hand interactions.

Measuring corticospinal excitability by means of transcranial magnetic stimulation (TMS) is a useful approach to determine whether a given task involves motor imagery. Indeed, several TMS studies have evidenced an increase in corticospinal excitability during explicit motor imagery tasks [7,8]. The aim of the present study was to provide evidence that action judgement involves motor imagery; if so, it should be accompanied by an increase in corticospinal excitability. To address this issue, we used TMS to measure changes in corticospinal excitability in participants, judging the compatibility between a given hand posture and the use of an object (object–hand interaction, OH task). These results were compared with those gathered in a control task in which participants had to judge whether two hands were in a similar posture or not (hand–hand interaction, HH task). The HH task was matched with the OH task in terms of visual display and verbal response. In both tasks, corticospinal excitability was compared with the motor-evoked potentials (MEPs) recorded during a dimming task to cancel out the possible effect of attention.

Under the assumption that the judgement of object–hand interactions involves implicit motor imagery, we predict that corticospinal excitability should increase in the OH task but not in the HH task. In contrast, a similar increase in both tasks would mean that changes in corticospinal excitability are due to unspecific processes in visual perception or decision making.

MATERIALS AND METHODS

The present experiment was performed in nine right-handed male volunteers, aged between 25 and 30 years and free of neurological history. Their ability to imagine movements was evaluated by means of the Vividness of Movement Imagery Questionnaire [9]. The experimental procedure was approved by the Ethics Committee of the Université catholique de Louvain and all participants gave their written, informed consent.

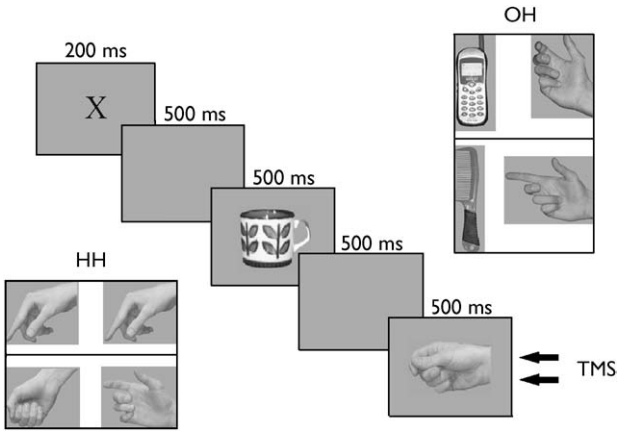

Fig. 1. Time course of the object–hand (OH) and hand–hand (HH) tasks. In the OH task, the participant had to decide whether the hand was in a posture compatible – or incompatible – with the normal use of the object. In the HH task, the participant had to determine whether the two hands were in the same posture. For each task, a pair of compatible (or identical) and incompatible (or different) visual stimuli are shown. Single-pulse transcranial magnetic stimulation (TMS) was delivered either 300 or 450 ms after the presentation of the second picture.

Tasks description: Experiments were performed in a dimly illuminated room. Participants sat comfortably in an armchair, 60 cm in front of a computer screen, with their elbows flexed and their hands half-pronated in a relaxed position. The participants were instructed to remain as relaxed as possible throughout the experiment and the background activity of one intrinsic hand muscle was monitored (see below).

Three tasks were investigated. (1) *The OH task*: a picture of a familiar object was presented on the computer screen, followed by that of a hand in a particular posture. The OH task consisted in deciding whether the hand was in a posture compatible with the conventional use of this object (Fig. 1). (2) *The HH task*: participants had to identify whether two hands presented sequentially were in the same posture (Fig. 1). It is noteworthy that, in a given trial, the two hands were always presented in the same orientation and that no mental rotation was required to perform this task. (3) *A dimming task*: participants had to detect the dimming of a central dot (2° red circle, 10% intensity reduction); this task was used as a baseline. In all three tasks, participants were required to give a verbal response, as quickly as possible. Verbal responses were recorded by means of a microphone and stored on a PC for offline analysis.

Experimental procedure: Before each task, participants performed 10 training trials. In addition, before the OH task, participants performed a *designation task* in which they had to name each object presented on the screen. The main experimental session consisted of 104 trials, 32 for the OH task (16 compatible OH combinations), 32 for the HH task (16 identical HH pairs) and 60 for the dimming task (3×20 trials). The HH task always preceded the OH task, with a dimming block before and after each one. For the OH and HH tasks, the blocks were designed so that the same response ('yes' or 'no') never occurred more than three times consecutively.

Each trial began with the display of a cross (200 ms) on the screen centre followed by a 500 ms mask. The object picture (OH) or the first hand (HH) was then presented for 500 ms, followed by another 500 ms mask, before a picture of a hand (OH and HH) was displayed for 500 ms. For the dimming task, the time between the stimulus presentation and dimming was randomly selected (range 2000–4000 ms). The delay between each trial was 3000 ms. The experiment was controlled with E-Prime V1.0 (2002, Psychological Software Tools, Pittsburgh, Pennsylvania, USA).

Transcranial magnetic stimulation: TMS was delivered using a Magstim 200 stimulator (Magstim Company, Dyfed, UK) through a 70 mm outer diameter figure-of-eight coil placed over the hand area of the left motor cortex. The coil was held tangential to the skull with the handle pointing laterally and backwards and its location was adjusted to optimize the MEP amplitude in the contralateral first dorsal interosseous (1DI) muscle. Once the optimal coil position was found, the 'hot spot' was marked on a closely fitting electroencephalogram cap and the motor threshold – defined as the lowest TMS intensity required to elicit five MEPs larger than 50 μV in a series of 10 stimulations – was determined. The TMS intensity was set at 120% of the motor threshold. MEPs were recorded from the right 1DI with surface electrodes. Electromyogram (EMG) signals were amplified (gain: 1k), high-pass filtered at 30 Hz (Neurolog, Digitimer, Hertfordshire, UK) and digitized online at 2 kHz using a personal computer with a CED 1401 interface (Cambridge Electronic Design, Cambridge, UK). For each trial, the EMG signal was acquired over a time window spanning the range of 200 ms before to 200 ms after TMS.

In the OH and HH conditions, the TMS was delivered, pseudorandomly, either 300 or 450 ms after the display of the second picture. In the dimming condition, TMS was delivered at random between the dot presentation and the dimming. TMS pulses were always separated by at least 5000 ms.

Individual EMG traces were checked to make sure that no movement was produced during the performance of the three tasks. Peak-to-peak amplitude of MEPs was then measured using Signal 2.08 (Cambridge Electronic Design, Cambridge, UK). Our interpretations of how the three different experimental conditions influenced the corticospinal excitability are based critically on whether the background activity in the 1DI differed during the time course of the tasks. Indeed, it is of paramount importance to rule out that the changes in MEP amplitude could be attributable to preexisting background EMG differences. To compare the EMG background between the three tasks, we rectified individual EMG traces and measured the area under the curve over the 200 ms before TMS. Analyses of the baseline activity before TMS demonstrated no difference between the three conditions as evidenced by a repeated-measure ANOVA with 'task' (OH, HH, dimming) as a within-participant factor [$F(2,16)=1.57$, ns].

Data analysis: Error trials and trials in which reaction time (RT) or MEP amplitude fell outside the individual mean ± 2 standard deviations (SD) limit were discarded. Statistical analyses were conducted on the remaining trials (93%). The MEP amplitude was then analysed by means of a repeated-measure ANOVA with 'task' (OH, HH, dimming) as a within-participant factor. Moreover, in order to assess an effect of the delay, a second repeated-measure ANOVA

was performed on the MEP amplitude with 'task' (OH vs. HH) and 'delay' (300 vs. 450 ms) as within-participant factors. Values are expressed as mean ± SD, throughout this paper.

RESULTS

The OH task yielded a mean RT of 762 ± 131 ms (mean ± SD, n=9) and an error rate of 5.2 ± 3.6%, whereas in the HH task, the mean RT and error rate were 595 ± 46 ms and 1.5 ± 1.04%, respectively. In the dimming task, used as a baseline, no error was detected and the mean RT was 397 ± 32 ms.

The first repeated-measure ANOVA with 'task' (OH, HH, dimming) as factor showed a significant main effect of the 'task' factor [$F(2,16)=4.03$, $p<0.038$]. As illustrated in Fig. 2, the mean MEP amplitude was larger in the OH task than in the HH task [$t(8)=-2.11$, $p<0.007$] and also the dimming task [$t(8)=3.12$, $p<0.034$]. No significant difference was observed between the HH and dimming tasks [$t(8)=-1.32$, ns]. The second repeated-measure ANOVA, with 'task' (OH vs. HH) and 'delay' (300 vs. 450 ms) as factors, showed a main effect of the task factor [$F(1,8)=9.65$, $p<0.014$] but neither a main effect of the 'delay' factor [$F(1,8)=0.05$, ns], nor two-way interaction between the 'task' and 'delay' factors [$F(1,8)=0.49$, ns].

DISCUSSION

In the present study, TMS was used to evaluate changes in corticospinal excitability while participants made judgements on object–hand interactions. Performing such judgements was found to increase corticospinal excitability in comparison with a control task matched in terms of visual display and verbal response, and a dimming task. Corticospinal excitability in these two tasks did not differ from each other. These results suggest that corticospinal excitability is specifically increased when predicting the outcome of an action, as a consequence of motor imagery.

In previous TMS studies, corticospinal excitability was found to have increased during explicit motor imagery tasks such as imagining flexion of fingers [7]. Our study extends these results to an action judgement task in which motor imagery was implicit [10]. The present electrophysiological results converge with the observations made in previous neuropsychological [6], behavioural [5] and neuroimaging studies [11] that highlight the role of motor imagery in representing the consequences of an action. In particular, our results corroborate the fact that motor imagery is not limited to the covert activation of a stored motor plan, as initially proposed by Jeannerod [12]. Indeed, it is unlikely that a motor plan contains the action parameters specific to every object. Therefore, we assume that the motor imagery process was permeable to visual information that constrained the movement outcome. The finding that the motor imagery process can be influenced by proprioceptive information relative to hand posture is consistent with this view [13]. A further step would be to investigate the modulation of MEP amplitude by implicit motor imagery in close relationship with the constraints of the real action (i.e. object orientation, action timing or required force).

The strong effect of the OH task on corticospinal excitability may explain why visual perception of objects or rotation of three-dimensional abstract figures leads, under certain circumstances, to an increased activation of

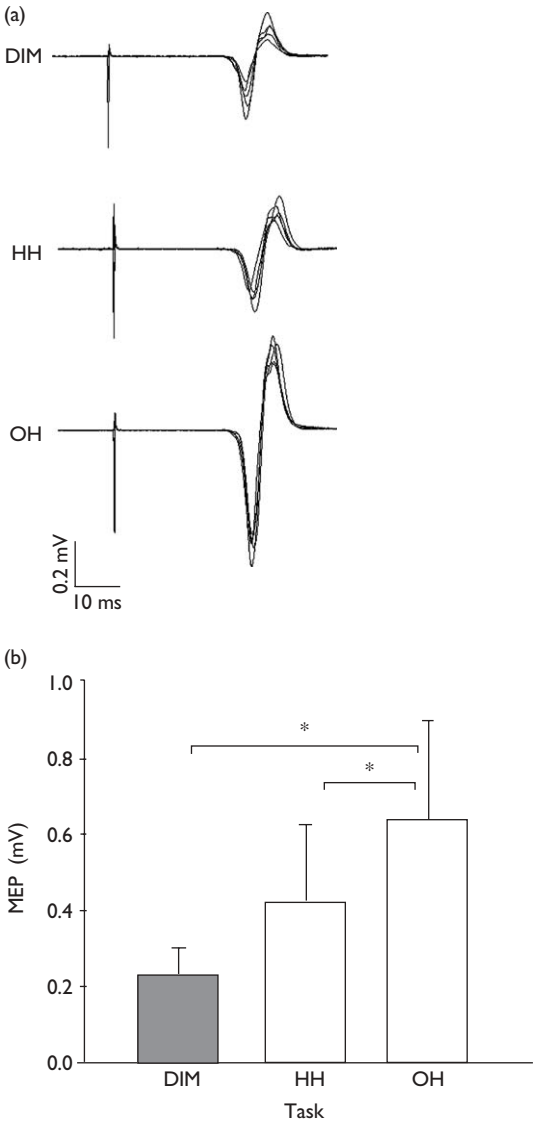

Fig. 2. Effect of the object–hand (OH) task on the corticospinal excitability. (**a**) Individual examples of motor-evoked potentials (MEPs) gathered during the dimming (DIM), hand–hand (HH) and OH tasks (n=5). (**b**) Mean MEP amplitude found in the three tasks for all nine participants.

motor areas [14,15]. This larger activity in motor structures may reflect the fact that, during such tasks, the participants also imagined themselves interacting with the object.

Because no difference in MEP amplitude was observed between the two delays of stimulation, the present results do not allow us to infer the time course of such an action simulation. However, the persistence of the effect 450 ms after the onset of the hand picture suggests that motor circuits remained active in the latest stages of the action simulation [16]. The question remains of whether the MEP increase consecutive to action judgement resulted from the direct or indirect activation of the primary motor cortex. A subcortical origin can be excluded on the basis of the highly semantic content of the task. Interestingly, patients with hemiplegia following lesions of the primary motor cortex are still able to imagine object–hand movements [17]. This

observation rather suggests that corticospinal excitability enhancement during action judgement arises from connections between the motor hand area and non primary motor areas, such as the premotor and parietal cortices. Under this assumption, training action judgement should improve the rehabilitation of hemiplegic patients through indirect stimulation of the injured motor cortex (see [18]).

CONCLUSION

Our study provides the first neurophysiological evidence that predicting the consequences of an action involves implicit motor imagery.

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Acknowledgements: B. P. is a research assistant supported by a grant from the School of Medicine of the Université catholique de Louvain. M. A. is a research assistant at the Fonds National pour la Recherche Scientifique (FNRS). We are grateful to Julie Duqué and Marco Davare for their comments on an earlier version of this paper. This project was supported by a grant from the 'Fonds de la Recherche Scientifique Médicale' (FRSM) and the 'Fondation Médicale Reine Elisabeth' (FMRE).