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RESEARCH NOTE

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Lateralization in motor facilitation during action observation: a TMS study

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Abstract Action observation facilitates corticospinal excitability. This is presumably due to a premotor neural system that is active when we perform actions and when we observe actions performed by others. It has been speculated that this neural system is a precursor of neural systems subserving language. If this theory is true, we may expect hemispheric differences in the motor facilitation produced by action observation, with the language-dominant left hemisphere showing stronger facilitation than the right hemisphere. Furthermore, it has been suggested that body parts are recognized via cortical regions controlling sensory and motor processing associated with that body part. If this is true, then corticospinal facilitation during action observation should be modulated by the laterality of the observed body part. The present study addressed these two issues using TMS for each motor cortex separately as participants observed actions being performed by a left hand, a right hand, or a control stimulus on the computer screen. We found no overall difference between the right and left hemisphere for motor-evoked potential (MEP) size during action observation. However, when TMS was applied to the left motor cortex, MEPs were larger while observing right hand actions. Likewise, when TMS was applied to the right motor cortex, MEPs were larger while observing left hand actions. Our data do not suggest left hemisphere superiority in the facilitating effects of action observation on the motor system. However, they do support the notion of a sensory-motor loop according to which sensory stimulus properties (for example, the image of a left hand or a right hand) directly affect motor cortex activity, even when no motor output is required. The pattern of this effect is congruent with the pattern of motor representation in each hemisphere.

Keywords Action observation · Sensory-motor systems · Hemispheres · Laterality

Introduction

Several studies have indicated that observing another person's actions activates one's own corticospinal system (Fadiga et al. 1995; Strafella and Paus 2000). A current hypothesis for this facilitation is that a premotor neural system is activated not only during action execution, but also during action observation (Gallese et al. 1996; Rizzolatti et al. 1996; Rizzolatti and Arbib 1998). First discovered in monkey premotor areas, these neurons fire when the animal makes a goal-directed action as well as when it observes similar actions made by others. Brain imaging data suggest similar neuronal properties in human premotor areas (Iacoboni et al. 1999; Rizzolatti et al. 2001). A behavioral counterpart of these neural mechanisms has been suggested by psychological data supporting the existence of a body schema used for encoding body position for both self and others (Reed and Farah 1995).

One property of this corticospinal facilitation during action observation is its muscle specificity. That is, motor-evoked potentials (MEPs) are facilitated only in the muscles involved in a particular observed action (Fadiga et al. 1995; Strafella and Paus 2000). The question we ask here is whether the lateralization pattern of corticospinal facilitation is similar to the known lateralization

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pattern for motor control. That is, would each hemisphere be most activated by observation of actions performed by the contralateral hand? If this pattern for motor control holds for the corticospinal facilitation observed during action observation, we would expect that not only each hemisphere is activated most by observation of the hand it controls, but that the preference for the contralateral hand is less robust for the dominant left hemisphere, which is known to have motor representation for both sides of the body (Kim et al. 1993; Chen et al. 1997).

The question of laterality for motor facilitation during action observation is central not only for understanding the representation (contralateral, ipsilateral, or bilateral) of the premotor areas, but also for understanding how this neural mechanism is associated with other cognitive functions. The cerebral hemispheres are considered to have different specializations and serve different functions. Generally, the right hemisphere is spatial and holistic while the left hemisphere is linguistic and analytical (Levy et al. 1971; Zaidel 1978). The finding of an asymmetry in the corticospinal facilitation obtained during action observation in the two hemispheres could, therefore, reflect a functional specialization of the premotor system mediating such effects. It has been proposed that the observation/execution matching system in premotor areas may reflect an evolutionary precursor of neural systems facilitating communication, and hence language (Rizzolatti and Arbib 1999), which is typically regarded as a left hemisphere function, even though evidence for right hemisphere language competence has been accumulating over the years (Iacoboni and Zaidel 1996; Giora et al. 2000). On the other hand, actions unfold in space, and space processing is considered typically a right hemisphere function. Thus, a more robust corticospinal facilitation during action observation in the left hemisphere would suggest the neural system mediating this effect might be linked to language. In contrast, a more robust corticospinal facilitation during action observation in the right hemisphere would suggest that the neural system mediating this effect might be linked to spatial processing.

We examined these issues using single-pulse transcranial magnetic stimulation (TMS) over the primary motor cortex. This area is activated by action observation (Fadiga et al. 1995) and is located only one synapse away from premotor areas endowed with action observation/execution matching properties (Gallese et al. 1996; Rizzolatti et al. 1996; Iacoboni et al. 1999). Although the TMS-induced facilitation should be considered a corticospinal effect since we stimulate the motor cortex and observe motor-evoked responses, converging evidence suggests that the facilitating effect occurs at a cortical level rather than at a spinal level (Hari et al. 1998; Nishitani and Hari 2000; Strafella and Paus 2000; Baldissera et al. 2001). This makes it plausible to test hemispheric effects with the single-pulse TMS technique over the motor cortex.

It has been suggested that premotor neurons with observation/execution matching properties are activated by goal-oriented movements rather than by movements in general (Gallese et al. 1996; Rizzolatti et al. 2000). In studies with children, Bekkering and colleagues (2000) have found imitation to be guided by goals and those goals, in turn, may be indicated by the simple presence of dots on a table to which one is asked to reach. Similarly, in a recent study, Koski et al. (2002) found that the presence of a red dot toward which a finger moves produces activation of motor areas. Consequently, to maximize the facilitation observed during action observation, we presented to our subjects finger movements toward a red dot.

Materials and methods

Subjects

Sixteen healthy volunteers (eight males, eight females; mean age 26 years, range 19–38 years) were studied. All subjects were right-handed (all scored 11 or more, out of a maximum of 13 points) according to a modified Oldfield Handedness Questionnaire (Oldfield 1971) and were naive to the purpose of the study. The subjects were screened for neurological, psychiatric, and medical problems, and contraindications to TMS (Wassermann 1998). A brief neurological examination was also performed on each subject. The UCLA Institutional Review Board approved the study and written informed consent was obtained from all subjects. Therefore, this study was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Task

Subjects were seated 57 cm away from a computer monitor with a custom-made forehead and chin rest fixed to a coil holder. Participants observed a hand movement or a control object movement on the computer screen. The hand on the computer screen (either left or right) was positioned so that the back of the hand was shown and the fingers were directed upward. The index finger of each stimulus hand moved toward a red dot every 600 ms for a total time of 6 s/trial (Fig. 1). Each condition (right hand stimuli, left hand stimuli) consisted of 20 pseudorandomly presented trials.

Transcranial magnetic stimulation

To measure MEPs, we placed two 10-mm gold surface electrodes on the belly and tendon of each subject's right (or left) first dorsal interosseus (FDI) muscle. A Velcro ground electrode was placed

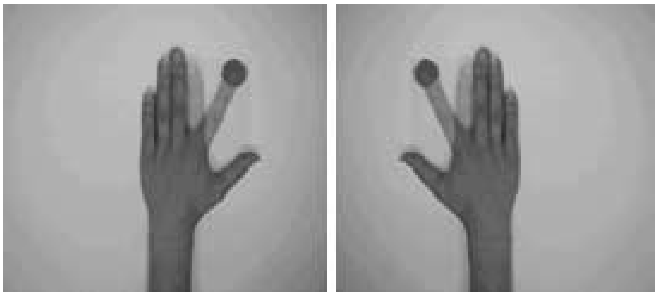

Fig. 1 Conditions observed by the participants: *left* left hand stimuli, *right* right hand stimuli. The index finger of the hand stimuli moved toward the red dot in the experimental conditions. All stimuli were presented in color

on the right (or left) upper arm. All of these sites were appropriately cleansed with alcohol prior to electrode attachment.

Single pulses of TMS were delivered through a 90-mm angled figure-of-eight coil using the Cadwell High Speed Magnetic Stimulator to the left (or right) "optimal scalp site". This was defined as the scalp position and coil orientation where TMS-induced MEPs were maximal in the FDI muscle. Motor-evoked potentials were collected (amplification: ×2,000–5,000; band pass: 0.3–3,000 Hz; digitization: sampling rate of 1 kHz/channel). The motor threshold (MT) was defined as the minimal intensity that induced MEPs greater than 50μ V peak-to-peak amplitude in at least five out of ten trials. Single-pulse TMS was delivered at 120% of the subjects' MT for all trials. Twenty MEPs were collected for resting baseline and for all conditions. The order of the hemisphere to be stimulated (left or right) was counterbalanced across subjects with a rest period between the two sessions.

Data analysis

Peak-to-peak amplitudes of the MEPs were measured and mean averages were calculated for baseline and for each of the three conditions. Since MEP size is known for its large interindividual variability (Rossini and Rossi 1998), MEP size was normalized in order to make them comparable across subjects. Percent change of the mean MEP size for each of the two experimental conditions from the mean MEP size for the control condition was calculated. Data were analyzed using a repeated measures three-way ANOVA [stimulus type (left hand, right hand) × hemisphere (left, right) × sex (male, female)]. All data from the subjects, except for subject 11, which had unadjustable background noise, were included in the analysis.

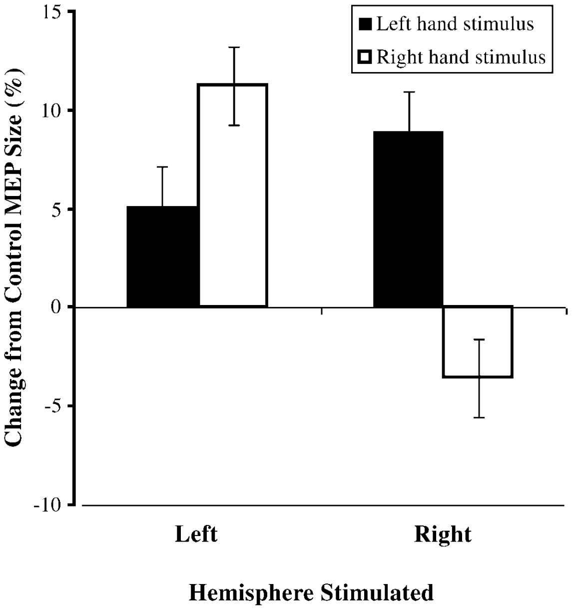

Fig. 2 Mean percent change of motor-evoked potential (MEP) size from control trials across subjects during observation of hand actions. The interaction between stimulus type and hemisphere is significant, $P=0.014$. The right hemisphere is especially sensitive to stimulus type, showing greater MEP sizes during observation of the contralateral hand as compared to the ipsilateral hand, $P=0.018$

Results

All subjects completed the session without problems. On average, MT for both the left and right hemisphere was found to be 53% of maximum stimulator output. A significant interaction between stimulus type and hemisphere was found, with each hemisphere showing greater excitation during the observation of actions conducted with the contralateral hand, $P=0.014$, $F(1,13)=7.99$ (Fig. 2). Thus, when TMS was applied to the right hemisphere, MEP sizes were largest to observation of left hand stimuli and when TMS was applied to the left hemisphere, MEP sizes were largest to observation of right hand stimuli. Mean contrasts of this interaction indicated that the non-dominant right hemisphere showed the greatest sensitivity for this effect. The right hemisphere was significantly more activated by left hand stimuli than right hand stimuli, $P=0.018$. The dominant left hemisphere was more activated during action observation of right hand stimuli, but this did not reach significance, $P=0.22$. Another mean contrast further elucidated this effect, showing a significant difference for right hand stimuli between the two hemispheres, $P=0.0078$. By contrast, there was no significant difference for left hand stimuli in the two hemispheres, $P=0.40$. Finally, no main effect for hemisphere was found, $P=0.31$, $F(1,13)=0.90$, nor were there any other significant effects or interactions. In particular, there were no main effects or interactions due to sex.

Discussion

This study addresses hemispheric specialization for corticospinal facilitation obtained during action observation. Specifically, we asked two questions: (1) does this facilitation follow each hemisphere's normal pattern of lateralized motor representation and (2) is corticospinal excitability during action observation more robust in one hemisphere as compared with the other.

Each hemisphere predominantly has motor representation for the contralateral hand. For right-handers, this contralateral representation is stronger for the right hemisphere; the dominant left hemisphere is known to have some level of bilateral motor control, even though the contralateral hand is still more strongly represented than the ipsilateral one (Kim et al. 1993; Chen et al. 1997). According to our findings, the same pattern of motor representation holds for action observation. Each hemisphere was more strongly activated when viewing actions conducted by the contralateral hand, and this effect was larger for the non-dominant right hemisphere than for the dominant left hemisphere.

Our results are further in accord with previous findings for a "sensory-motor loop" hypothesis according to which visual stimulus properties (for example, being a left hand or a right hand) directly affect motor cortex activity, even when no motor output is required. The pattern of this effect is congruent with the pattern of motor representation in each hemisphere, a finding that supports the notion of a shared representation for observed and performed actions. We believe that this pattern of lateralization is eminently driven by properties of primary motor cortex. In fact, at the level of premotor areas, the areas thought to be the ones that respond primarily to action observation, motor control is known to be largely bilateral (Passingham 1993). We have recently performed a meta-analysis of 58 subjects studied with fMRI while observing hand actions. We observed in this large dataset bilateral activation of inferior Brodmann area 6, Brodmann area 44, and Brodmann area 45 (Iacoboni 2002). Thus, it is likely that the pattern of lateralization observed here reflects more primary motor properties than premotor properties. This is not to say that the effect of corticospinal facilitation during action observation typically observed by single-pulse TMS is primarily originating at primary motor cortex level. It is conceivable that the effect is originated by premotor activation during action observation. This premotor activation would feed into primary motor cortex, changing the corticospinal excitability induced by TMS over primary motor sites.

Our results concur with a study on mental imagery by Fadiga and colleagues (1999), which explored issues of laterality in the motor system using TMS. Participants were asked to imagine either left or right hand movements as the researchers stimulated each motor cortex with TMS. Their result indicated that while MEP amplitudes increase when participants imagine ipsilateral and contralateral movements during left hemisphere stimulation, during right hemisphere stimulation only imagery of the contralateral hand increased MEP amplitude. These findings are precisely in accord with our results for action observation. Together, they suggest a parsimony for processing in the motor system by which motor output, mental imagery, and action observation seem to utilize the same neural representation. They may further indicate that mental imagery is a form of action observation. In this view, action observation would precede mental imagery in the evolutionary sequence. That is, through evolution, first there was action, then the ability to observe action, and finally the ability to imagine action, with each evolutionary step constructed on the neural mechanisms that preceded it. The ability to utilize constructively these imagined actions – thought – may have been placed atop these mechanisms as a final evolutionary component.

Our data do not support a difference for action observation between the left and right hemisphere. This may seem contradictory to PET studies by Grafton et al. (1996) and Rizzolatti et al. (1996) that show left hemisphere activation in the mirror system, albeit in areas such as inferior frontal cortex, superior temporal sulcus, and supplementary motor areas rather than motor cortices per se. The main methodological difference between the previous studies and the current study is that the previous studies measured cerebral blood flow, an indirect measure of brain activity, while the current study explored brain activity via direct stimulation of motor areas. Finally, the effect observed in previous imaging studies was at premotor level, whereas here we are directly stimulating the primary motor cortex. Also, one should be aware that lateralized findings in fMRI studies may simply reflect thresholding effects; lowered thresholds may reveal bilateral activations. For instance, the lateralized activation in frontal and parietal areas reported in our fMRI study of imitation (Iacoboni et al. 1999) become bilateral at a lower statistical threshold.

However, the lack of a left hemisphere lateralization for corticospinal facilitation obtained during action observation should not be necessarily considered evidence against a link between language and the observation/execution matching system that presumably subserves such facilitation. It is well known that the right hemisphere contributes to language processing as well, especially for lexical and pragmatic processing (Iacoboni and Zaidel 1996; Giora et al. 2000). Both lexical access and pragmatics are linguistic components relevant to social aspects of language. The observation/execution matching system is also thought to be relevant to social cognition, such as understanding of intentional relations that are at the core of human social behavior (Iacoboni 2002). It is conceivable that the observation/execution matching system, if it is a precursor for language, is involved mostly in aspects of language that have to do with social behavior more than, say, with grammar.

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