NeuroImage 146 (2017) 770–777

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

# TMS of supplementary motor area (SMA) facilitates mental rotation performance: Evidence for sequence processing in SMA

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ARTICLE INFO

*Keywords:*
Mental rotation
TMS
Supplementary motor area
SMA
M1
Motor area
Imagery
Visuo-spatial
Accumulator
Sequence processing
Transcranial magnetic stimulation

ABSTRACT

In the present study we applied online transcranial magnetic stimulation (TMS) bursts at 10 Hz to the supplementary motor area (SMA) and primary motor cortex to test whether these regions are causally involved in mental rotation. Furthermore, in order to investigate what is the specific role played by SMA and primary motor cortex, two mental rotation tasks were used, which included pictures of hands and abstract objects, respectively.

While primary motor cortex stimulation did not affect mental rotation performance, SMA stimulation improved the performance in the task with object stimuli, and only for the pairs of stimuli that had higher angular disparity between each other (i.e., 100° and 150°).

The finding that the effect of SMA stimulation was modulated by the amount of spatial orientation information indicates that SMA is causally involved in the very act of mental rotation. More specifically, we propose that SMA mediates domain-general sequence processes, likely required to accumulate and integrate information that are, in this context, spatial. The possible physiological mechanisms underlying the facilitation of performance due to SMA stimulation are discussed.

## Introduction

Visuo-spatial processing is typically studied using variants of the classic Mental Rotation (MR) tasks, in which individuals are required to judge whether two objects, presented at different orientations, are the same or mirror images of each other (e.g., Shepard and Metzler, 1971; Shepard and Cooper, 1982). In these tasks, reaction times (RTs) are usually found to increase as a function of angular disparity between the objects, a phenomenon that has been taken as evidence that individuals mentally rotate the objects as if they were physically rotating them (e.g., Shepard and Cooper, 1982).

The neural basis of MR has received considerable attention in recent years and has been investigated with multiple modalities, including magnetoencephalography (MEG), electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and transcranial magnetic stimulation (TMS) (e.g., Bode et al., 2007; Kawamichi et al., 2007; Milivojevic et al., 2009a; Vingerhoets et al., 2002; Zacks, 2008; Wraga et al., 2005). Although the contribution of parietal regions to MR processes is well-established (e.g., Harris and Miniussi, 2003; Jordan et al., 2001; Parsons, 2003; Zacks, 2008), the involvement of the motor system, including the primary motor cortex (M1), premotor regions, and the supplementary motor area (SMA), remains instead less clear. Studies have found that M1 plays a role in MR processes (e.g., Ganis et al., 2000; Pelgrims et al., 2011; Tomasino et al., 2005), whereas others did not show any causal involvement of M1 (Sauner et al., 2006), or interpreted M1 activation as epiphenomenal and/or the result of the spread of activation from adjacent and connected regions, such as the premotor regions (Bode et al., 2007; Eisenegger et al., 2007). Thus, M1 would not be essentially involved in MR tasks but would represent a subsidiary area, which is activated only because premotor areas are activated.

The involvement of premotor cortices and SMA has been found more consistently (e.g., Jordan et al., 2002; Lamm et al., 2007; Leek et al., 2016; Kosslyn et al., 1998; Wraga et al., 2005; see Zacks *for a review*). Nevertheless, their functional contribution to MR tasks is still debated and several hypotheses have been suggested (see, for example, Lamm et al. (2007)). In particular, according to the "motor imagery theory", activations of these areas may be due to the fact that participants imagine rotating their own hands/body parts to solve the tasks (e.g., Kosslyn et al., 2001; Vingerhoets et al., 2001, 2002; Wraga

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http://dx.doi.org/10.1016/j.neuroimage.2016.10.032
Received 26 May 2016; Accepted 18 October 2016
Available online 27 October 2016

et al., 2005; Zacks, 2008). By contrast, evidence from recent studies suggested that premotor and SMA activations do not reflect motor simulation, but are associated with MR per se (Lamm et al., 2007; Leek et al., 2016; Richter et al., 2000). More specifically, concerning the SMA involvement, the study by Richter et al. (2000) revealed that the duration of the BOLD (Blood-oxygen-level dependent) signal within SMA increased as a function of the time required to mentally rotating the stimuli. Furthermore, Ecker et al. (2006) found that the strongest correlation between the duration of MR operations and the time course of the hemodynamic response functions (HRF) occurred in the pre-SMA. Interestingly, linear relations between BOLD signal and angular disparity were found within pre-SMA: the larger the angular disparity between the stimuli, the greater the pre-SMA activation (Milivojevic et al., 2009a). Finally, a recent study showed that activation of SMA, and more specifically the pre-SMA regions, during MR tasks was associated with domain-general sequential operations in visuo-spatial processing, such as the serial remapping of spatial positions as a function of the changes in stimulus orientation (Leek et al., 2016).

The present study aimed to investigate whether SMA plays a causal role in MR tasks. Therefore, we applied short TMS bursts to the left SMA while participants were engaged in MR tasks involving objects and hands as stimuli. Since previous studies revealed that pictures of hands implicitly trigger the use of motor imagery strategy and, consequently, the activation of motor regions to a greater extent than abstract pictures do (Kosslyn et al., 1998; Vingerhoets et al., 2001), we could make different predictions about the TMS effect. On the basis of the motor imagery theory, we should find an effect of SMA stimulation only in the task involving hand stimuli. By contrast, we should find a TMS effect in tasks involving both the hand and the abstract object stimuli if SMA mediates non-motor, visuo-spatial operations closely related to MR.

In this study we stimulated also the left M1, for two reasons. First, as SMA is connected with M1 (Narayana et al., 2012), a reasonable speculation is that a possible TMS effect observed when stimulating the SMA would be the result of the indirect modulation of M1 activity. Therefore, to control this aspect, both SMA and M1 were stimulated in separate sessions, and the effects compared.

Second, as mentioned above, there are contradictory results about M1 involvement in MR tasks. Therefore, this study could help determine whether M1 plays a crucial role in MR tasks or is merely a subsidiary area. One question is what the role of M1 during MR is. If M1 supports motor simulation, as proposed by the 'motor imagery theory' (Kosslyn et al., 2001; Vingerhoets et al., 2002), we should expect to observe an effect of M1 stimulation specifically in the task that includes hands as stimuli. By contrast, if M1 is not essential for successful MR performance (Eisenegger et al., 2007; Sauner et al., 2006), no TMS effect should be expected on MR task, either with hand or object stimuli.

## Materials and methods

### *Participants*

Sixteen students of the University of Padua, Italy, took part in the experiment (11 females and 5 males; mean age: 24.4 years (range: 21–30); Educational level: 16 years (range: 14–18)). Participants had normal or corrected-to-normal vision, and were right-handed according to the Edinburgh inventory (Oldfield, 1971). All were healthy, with no history of head injury or neurological, psychiatric, or physical illness and were all checked for TMS exclusion criteria (Rossi et al., 2009). No participant was a professional musician or athlete. They gave informed written consent before participating in the experiment. The study was carried out in accordance with the guidelines of the Declaration of Helsinki and was approved by the ethical committee of the Department of General Psychology, University of Padua.

### *Stimuli and procedure*

Participants were seated in front of a color monitor screen at a distance of about 60 cm. The experiment was run using the E-Prime software system. Two types of MR tasks were designed, involving pictures of objects and hands, and were administered in a counter-balanced order across participants. For each single participant, the order of task presentation was the same among the three TMS sessions. Therefore half of participants always started with the task including object stimuli, whereas the other half started with the task including hand stimuli. In both tasks, pairs of stimuli were simultaneously presented and could appear at different angles of orientation. Participants were asked to verbally report whether the stimulus presented on the right was the same or a mirror version of the stimulus on the left by saying "sì" (yes; *same* stimuli) or "no" (no; *mirror* stimuli). Verbal responses were recorded with a digital voice recorder.

The object stimuli were 3-D Shepard and Metzler-like object figures obtained from the dataset by Ganis and Kievit (2014). The objects were white on a black screen and had a natural-looking shading effect. Each object consisted of 7 to 11 cubes and was composed of 4 arms, connected end-to-end in a sequence.

The hand stimuli were 3-D pictures of upright hands, constructed with a digital camera and picture-editing software (Adobe Photoshop C24 Version 11.0). The hands were also white on a black background. As suggested by Ganis et al. (2000), in order to avoid visuo-motor interference, the stimulus on the left side was always a left hand whereas the stimulus on the right side was a left hand in 50% of the pairs and a right hand in the other 50%. Fig. 1 shows some examples of the pairs of stimuli and a schematic timeline of an experimental trial.

Seven different configurations of objects and hands were used to

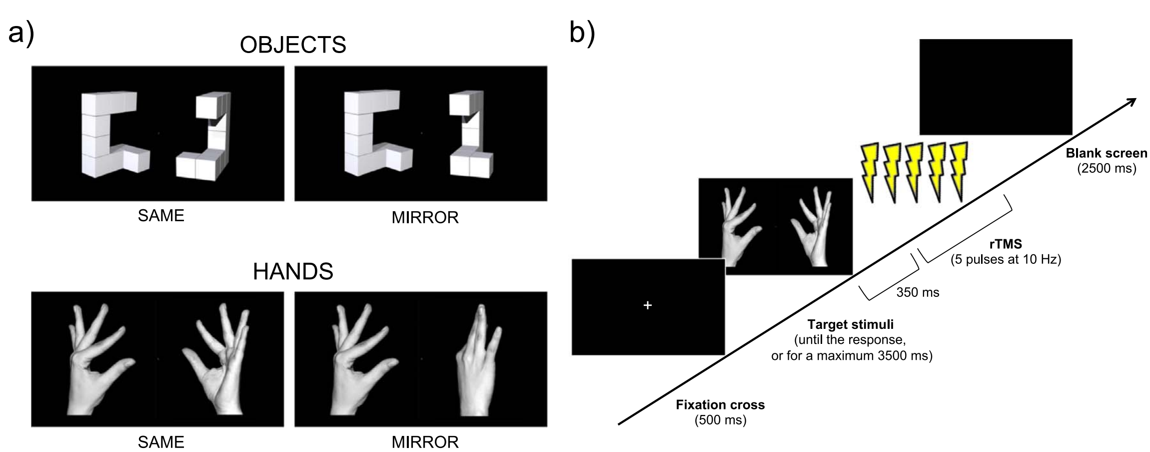


**Fig. 1.** Stimuli and Timeline. a) Example of object stimuli (upper panel) and hand stimuli (lower task), presented at 150° of angular disparity. The stimuli could be identical ("*same*") or mirror images of each other ("*mirror*"). b) A schematic illustration of the timeline of an experimental trial.