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MOTOR SYSTEM MODULATION FOR MOVEMENT DIRECTION AND ROTATION ANGLE DURING MOTOR IMAGERY

F. PIZZOLATO, M. FIORIO AND P. CESARI *

Faculty of Motor and Sport Science, Department of Neurological, Neuropsychological, Morphological and Movement Science, University of Verona, Italy

Abstract—Transcranial magnetic stimulation (TMS) studies have shown that the motor system is facilitated when we imagine performing motor actions. However, it is not clear whether the individual's motor system modulates bilaterally and selectively for task parameters, such as movement direction and amplitude. To investigate this issue, we applied single-pulse TMS over the left and right primary motor cortex (M1) of healthy subjects, who had to imagine grasping and rotating a clock hour hand, having a starting position at noon, towards four different times: 2, 5, 7 and 10 o'clock. Rotations could be in clockwise (2 and 5 o'clock) or counter-clockwise (7 and 10 o'clock) directions and could require small (2 and 10 o'clock) or large (5 and 7 o'clock) rotation angle. TMS motor-evoked potentials were recorded for three muscles, and movements were imagined with the right and left hands. Results showed that during motor imagery a mirroring pattern was present between the right and the left motor cortices, showing selective activation of the hand-intrinsic muscles spatially close to the direction of the imagined movement. Overall a higher activation for large and a lower activation for small rotation angle were found, but no selective muscle activity was present within the hand-intrinsic muscles for this parameter. Following these results we propose that during action imagination an internally coded covariance between movement parameters is present with a muscle-specific activation for movement direction.

Key words: transcranial magnetic stimulation, movement direction, rotation angle, motor cortex, imagination.

INTRODUCTION

Directing an action towards a particular point in space is presumed to involve neuronal events that transform visual information about target location into muscle activation, culminating in force production for limb displacement. As a whole, the process is supposed to elaborate an internal transformation of the target position, defined by the Cartesian coordinates, into the intrinsic muscle activity framework (Rizzolatti and Luppino, 2001). This sensory-motor transformation allows representing actions in terms of movement parameters, such as direction and amplitude. Understanding how these parameters are internally coded might carry relevant information about action planning and action execution.

Following the literature, there is noclear consensus in explaining the internal processes used to code different movement parameters. If on one side studies support the existence of a unique internal system for planning both movement distance and movement direction (Bhat and Sanes, 1998), on the other side there are evidences in favour of two independently controlled mechanisms one for movement direction and one for movement amplitude (Humphrey and Reed, 1983; Kurtzer et al., 2005; Scheidt and Ghez, 2007). In particular, transcranial magnetic stimulation (TMS) studies have shown that movement direction is the parameter encoded well before movement onset, by adding the notion that facilitation in the motor cortex appears earlier for the agonist muscle (the prime mover), compared to the antagonist one (the non-prime mover) (Sommer et al., 2001). On the contrary, no specific modulation has been detected in the motor system resonance while participants were observing changes in movement amplitudes (Romani et al., 2005).

It is important to underline though that the majority of researches has been devoted in understanding the neural coding for movement direction. In this regard, results are consistent in showing activity of several neural populations registered from all the major motor components of the central nervous system for coding this movement parameter (Georgopoulos et al., 1986, 1989; Ashe and Georgopoulos, 1994; Georgopoulos, 1995; Georgopoulos and Pellizzer, 1995; Johnson et al., 1999; Moran and Schwartz, 1999a,b). On the contrary, less has been reported for movement amplitude, but results suggest the existence of a certain degree of co-variation between movement direction and amplitudes (Fu et al., 1993, 1995; Bhat and Sanes, 1998; Messier and Kalaska, 2000; Fabbri et al., 2012) even though each parameter seems timed and has a critical influence at different action phases from its preparation to its execution (Messier and Kalaska, 2000). Several behavioural studies reported direction and amplitude as independently organised (Gordon et al., 1994a,b; Messier and Kalaska, 1997), however there are also evidences that the same neurons are active for both parameters during action preplanning (Ghez et al., 1997). Concerning the processing over time of these two movement parameters,

*Corresponding author. Address: Via Casorati 43, 37131 Verona, Italy. Tel: +39-0458425131; fax: +39-0458425124.
E-mail address: paola.cesari@univr.it (P. Cesari).

Abbreviations: ADM, Abductor Digiti Minimi; ANOVA, analysis of variance; EMG, elecromyography; FDI, First Dorsal Interosseous; FDS, Flexor Digitorum Superficialis; M1, primary motor cortex; MEPs, motor-evoked potentials; OSP, optimal scalp position; rMT, resting motor threshold; TMS, transcranial magnetic stimulation.

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while some studies report a hierarchical organisation, where direction is modulated before amplitude (Larish and Frekany, 1985), some others show that direction could be processed either simultaneously or even after amplitude (Rosenbaum, 1980; Favilla and De Cecco, 1996; Ghez et al., 1997).

In order to unravel whether these movement parameters are independently pre-planned, TMS is an appropriate technique since it allows measurements of brain activation either before subjects perform a movement or when they internally simulate the movement by imagining it or observing it (Fadiga et al., 1995, 1999; Brighina et al., 2000; Strafella and Paus, 2000; Gangitano et al., 2001, 2004; Maeda et al., 2001, 2002; Aziz-Zadeh et al., 2002; Koski et al., 2002; Romani et al., 2005). As such, far more appropriate would be to measure participant's motor system activity while they imagine performing a specific movement. Indeed, what differs between action observation and action imagination is that while during the former participants are required to observe an action that is already defined in terms of movement characteristics such as direction, amplitude, velocity, and so on, during action imagination they are free to define these parameters in their own way. For this reason, action imagination represents an ad hoc modality for testing a self-triggered internal simulation of an action indicating whether the motor system resonates preferentially for movement direction or amplitude, without any external constraints.

Here we performed an experiment to investigate whether the selection of a task parameter, such as movement direction or movement amplitude, differently modulates the cortico-spinal system. We applied TMS while subjects imagined rotating the hour hand of a clock. Rotations could occur in two different directions, clockwise or anti-clockwise and with two different rotation angles, large or small. Furthermore, since it has been shown that the dominant arm exhibits a distinct advantage over the non-dominant arm in controlling the limb dynamics (Bagesteiro and Sainburg, 2002; Sainburg, 2002), we also aimed at investigating a potential role of hand dominance and hemispheric specialisation in this task, by asking subjects to imagine the actions with the dominant and non-dominant hand. Furthermore, in a control condition, we asked subjects to actually perform the same movement imagined to check whether the same muscle-specific activity was present for both movement parameters during action execution as well.

This design made it possible to investigate different issues: (i) whether during movement imagination a coherent neuromuscular pattern encodes specifically movement direction or rotation angle or both; (ii) whether there exists a somato-topic organisation whereby muscle activation follows a spatial congruency with movement direction and rotation angle; (iii) whether there might be a privileged pattern for the dominant compared to the non-dominant hand; (iv) whether the same pattern of activation was present by comparing action imagination with action execution.

As consistently reported in the literature we expect that during action imagination, among multiple organising principles (Aflalo and Graziano, 2006), a somato-topic organisation for movement direction would be encoded in the primary motor cortex (Georgopoulos et al., 1986, 1989; Ashe and Georgopoulos, 1994; Georgopoulos, 1995; Georgopoulos and Pellizzer, 1995; Johnson et al., 1999; Moran and Schwartz, 1999a,b; Cowper-Smith et al., 2010; Eisenberg et al., 2010; Toxopeus et al., 2011), thus resulting in specific activation of the muscles more strictly related to the imagined direction. With respect to rotation angle, we have a less clear expectation due to the less-pronounced consensus evidenced in the scientific community (Fu et al., 1993, 1995; Bhat and Sanes, 1998; Messier and Kalaska, 2000; Fabbri, 2011). In the current study we used TMS during action imagination to determine whether the same covariance between neurons sensitive to direction and rotation angle is present in the primary motor cortex in absence of an actual action performance.

EXPERIMENTAL PROCEDURES

Participants

Seventeen right-handed (Oldfield, 1971) healthy subjects (12 men and 5 women) ranging in age from 21 to 32 years (mean age = 25.4 years, SD = 6.04 years) participated in the study. All participants were unaware of the purposes of the experiment and none had neurological, psychiatric, or any other medical problems, nor did they have any side-effect reaction to TMS (Wassermann, 1998). There were no reports or observations of any discomfort or adverse effects during TMS. Before entering the laboratory, participants gave their written-informed consent. The procedures, approved by the local ethics committee, were in accordance with the ethical standards of the 1964 Declaration of Helsinki.

Procedure

The seventeen participants were divided in two groups: 8 (mean age = 24.4 years, SD = 5.64 years) were asked to imagine performing the action with their left hand while the right motor cortex was stimulated via TMS, and 9 (mean age = 26.6 years, SD = 6.51 years) were asked to imagine performing the action with their right hand while the left motor cortex was stimulated via TMS. All the participants were individually tested in the laboratory of the University of Verona. During motor imagery, subjects kept their hand and forearm comfortably lying on a cushion to avoid any unwanted muscular contraction.

On the table there was an analogue clock presenting in its centre a knob connected with the clock hour hand such that by rotating the knob the hour hand clock was rotating as well. The knob was a sphere that ranged in diameter from 5 to 6 cm. The diameter of the sphere was selected for each individual so that it was 1/3 of the length of the participant's hand, allowing a comfortable contact of the five digits of one hand with the object's surface. The participants were required to imagine grasping and rotating the knob, having an initial position at noon, in a clockwise or in an anti-clockwise direction at four different clock-time conditions (2, 5, 7 and 10 o'clock), presented in a random order (Fig. 1A).

The instructions were to imagine the action by using a first person perspective and to feel the action by using a kinaesthetic strategy while observing the sphere. Before data collection, the subjects were trained to execute the action in 12 trials, 3 for each clock position. The training allowed subjects to get familiarised with the task and, more importantly, to learn how to perform the action within a certain time window. The timing was defined by consecutive vocal commands: at first a ''ready'' command was