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A sensorimotor network for actions and intentions reading: a series of TMS studies.

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1 Overview

Information relevant for our social life are immediately processed by our brain. When we walk in the street we easily and quite automatically adjust our path to avoid colliding other people. Several social activities like working in a group, playing a sport, talking with people and many others, all require the ability to carefully read others movements. Thus, kinematics and postural information of others' body are a fundamental medium for good survival in our social environment.

Along the reading of this manuscript a series of extensive and novel studies will describe the role of sensorimotor cortices and their differential contribution in specific action observation tasks. By means of transcranial magnetic stimulation (TMS) we tested in healthy subjects both low and high cognitive level processes that may require areas of the action observation network.

Study1 investigated the modulation of the motor cortex during the observation of actions' pictures. When we observe a picture of a sport player we can immediately infer a huge amount of information mainly conveyed by the only body posture of the actor. We can feel the strength he is applying to his legs, we can foresee the direction where he was going to, we can infer his goals and intentions and further, his possible next moves. This is possible since the perception of a moving object or creature is distorted forward along its actual or implied motion path and this ability of the human brain is fundamental to enable the anticipation of forthcoming actions' positions.

The observation of static snapshots that imply body actions activates the human motor system but whether extrapolation of dynamic information and motor activation are higher for upcoming than past action phases is still unknown. In Study1 we demonstrated that by using single-pulse TMS the observation of start and middle phases of grasp and flick actions engendered a significantly higher motor facilitation than observing their final postures.

While in the first study healthy participants were required to passively observe static pictures, in Study2 we described the involvement of primary somatosensory cortex in a weight judgment task. Everyone "felt" the strength and fatigue a weightlifter is experiencing when lifting more than 100kg, but how can we understand the weight of a lifted object by simply observing the kinematic behaviour of a human lifter?

A network of areas in the parietal and premotor cortices are active both during action execution and observation, this suggests that we might understand the actions of other people by simulating what we would do in the same circumstances. Although neurophysiological and imaging studies show an involvement of somatosensory cortices (SI) during action observation and execution, it is not clear whether SI plays an essential role in understanding the observed action. To test if SI is required for action understanding we used off-line transcranial magnetic continuous theta-burst stimulation (cTBS) just before a weight judgment task. Participants observed an actor lifting a box and judged the box weight. We delivered sham- and active- cTBS over the hand region of SI and over the motor cortex (M1) and the superior parietal lobule (SPL). Importantly we observed that Active-cTBS over SI, but not over M1 or SPL, impaired the task performance relative to sham conditions.

The third and final set of experiments (Study3) tested whether areas linked to the action observation network are crucial also for higher level of cognitive processing. Whether the first two studies described the recruitment of primary motor and sensory cortices respectively in the observation of static pictures (Study 1) and in the extrapolation of sensory information from action observation (Study 2) in this last study we provided evidence that human ability to successfully read others' intentions, in particular deceptive intentions, requires the integrity of the anterior node of the action observation system. This study is intrinsically relevant since the ability to infer deceptive intents from nonverbal behavior is critical for social interactions. By combining single-pulse and repetitive transcranial magnetic stimulation (TMS) in healthy humans, we provided both correlational and causative evidence that action simulation is actively involved in the ability to recognize deceptive body movements. We recorded motor-evoked potentials during a faked-action discrimination (FAD) task: participants watched videos of actors lifting a cube and judged whether the actors were trying to deceive them concerning the real weight of the cube. Seeing faked actions facilitated the observers' motor system more than truthful actions in a body-part specific manner, suggesting that motor resonance was sensitive to deceptive movements. Furthermore, we found that

TMS virtual lesion to the anterior node of the action observation network, namely the left inferior frontal cortex (IFC), reduced perceptual sensitivity in the FAD task. In contrast, no change in FAD-task performance was found after virtual lesions to the left temporo-parietal junction (TPJ, control site). Moreover, virtual lesion to the IFC failed to affect performance in a difficulty-matched spatial-control task that did not require processing of spatio- temporal (acceleration) and configurational (limb displacement) features of seen actions which are critical to detecting deceptive intent in the actions of others. These findings indicate that the human IFC is critical for recognizing deceptive body movements and suggest that FAD relies on the simulation of subtle changes in action kinematics within the motor system.

2 Study1: Simulating the Future of Actions in the Human Corticospinal System

2.1 Introduction

The full sequence of motion is rarely visible during interactions with a dynamic world. Yet, the human visual system is inherently equipped with the ability to complete missing information (Pessoa et al. 1998; Komatsu 2006). Even when there is no obstacle to our view, the intrinsic delay of our perceptual processing and our motor responses requires an anticipatory representation of the motion sequence in order to interact optimally with moving objects or creatures (Schutz-Bosbach and Prinz 2007; Perrett et al. 2009). This top-down modulation of visual perception may use previous experiences and knowledge on motion to predict and anticipate the forthcoming position of moving entities and thus create a representation of events occurring in the near future (Ingvar 1985). Behavioral studies in humans, for example, have shown that memory for the final position or configuration of a moving object is distorted forward along its path of motion, an effect known as representational momentum (Freyd 1983). In a typical representational momentum experiment, a series of snapshots eliciting the perception of apparent motion is presented. Observers show a tendency to mislocalize the final position of the moving entity further along the anticipated trajectory. This effect has been demonstrated with a variety of stimuli including dot patterns (Finke and Freyd 1985), common objects (Finke and Shyi 1988), dynamic facial expressions (Yoshikawa and Sato 2008), and human figures (Verfaillie and Daems 2002). It is worth noting that the effect is found even when the actual motion is not present but only implied by static images of moving entities (Freyd 1983). The anticipatory representation of motion demonstrates the ability of our brain to bridge discontinuities in visual inputs by using internal models of the physical rules that govern object motion in the environment, for example, gravity (Hubbard 2005; Zago and Lacquaniti 2005; Motes et al. 2008). Importantly, the perception of movements performed by conspecifics may also rely on the motor representations used during planning and execution of actions (Verfaillie and Daems 2002; Flach et al. 2004; Ramnani and Miall 2004). Neuroimaging studies in humans (Kourtzi and Kanwisher 2000; Senior et al. 2000) demonstrate that viewing photographs of humans, animals, objects, and natural scenes with implied motion activates the same medial temporal/medial superior temporal area (MT/MST complex) that is also involved in processing real motion (Zeki et al. 1991; Dupont et al. 1994; Tootell et al. 1995). Furthermore, studies in humans (Krekelberg et al. 2005; Lorteije et al. 2007) and monkeys (Krekelberg et al. 2003) suggest that the same populations of cells in extrastriate visual areas code for both implied and real motion. Representational momentum effects, however, seem to involve a larger network of higher-order prefrontal and parietal areas (Amorim et al. 2000; Rao et al. 2004) that may interact with the MT/MST complex during extrapolation of motion information from static images. Moreover, still images implying biological motion activate the lateral occipitotemporal junction (Peigneux et al. 2000), the parietal cortex (Hermsdo rfer et al. 2001), and the superior temporal sulcus (Peuskens et al. 2005). In a similar vein, neurons in the monkey’s superior temporal cortex respond to the presentation of both moving body parts and static images of body postures implying preceding action (Jellema and Perrett 2003a, 2003b; Puce and Perrett 2003; Barraclough et al. 2006; Perrett et al. 2009). By using single-pulse transcranial magnetic stimulation (TMS), we have previously shown that passive viewing of static images implying body actions triggers activation of the human motor system (Urgesi, Moro, et al. 2006). This suggests that the frontal node of the frontoparietal mirror neuron system that matches action observation and execution (di Pellegrino et al. 1992; Rizzolatti and Craighero 2004) may play a major role in the extrapolation of dynamic information from static images that imply body actions. Previous TMS studies have shown that mirror motor facilitation is specific to the muscle involved in the observed action (Fadiga et al. 1995; Romani et al. 2005; Urgesi, Candidi, et al. 2006), is comparable for intransitive body movements and goal-directed actions (Fadiga et al. 1995, 2005; Cattaneo et al. 2009) and can be modulated by the temporal dynamics of the observed actions, simulating the time course of activations during movement execution (Baldissera et al. 2001; Gangitano et al. 2001, 2004; Borroni et al. 2005; Montagna et al. 2005). These findings suggest that mirror facilitations represent action kinematics, more than the goal or the intention beyond an action. Repetitive TMS over the ventral premotor cortex ceased the increase of motor excitability during action observation, suggesting that computation carried out in the frontal node of the mirror neuron system are critical for mirror motor facilitation to occur (Avenanti et al. 2007). These results are well in keeping with a hierarchical model of human action understanding in which the frontal and parietal nodes of the human mirror neuron system have different roles in encoding the action kinematics and the action goals or intentions, respectively (Grafton and Hamilton 2007). Notably, mirror motor facilitation of the first dorsal interosseous (FDI) muscle was present during observation of static snapshots representing the middle postures of a mimicked grasping action, where the hand had maximal grasp aperture (Urgesi, Moro, et al. 2006). In contrast, it was absent not only during observation of a resting, relaxed hand but also during observation of the end posture of the same action, where the hand had maximal finger closure. What remains unknown is whether mirror motor facilitation is selectively linked to the extraction of dynamic information about the upcoming or past action phases. In particular, no study has thus far addressed the issue of whether the motor facilitation found during observation of implied action stimuli derives from mere reading out of muscle contraction and joint configuration or from the anticipatory simulation of the temporal deployment of the action depicted in a given snapshot. Here, we addressed this issue by exploring any differential modulation of motor potentials evoked by single-pulse TMS while participants observed static snapshots representing the start, middle, or end postures of 2 different right-hand actions: grasping a ball (grasp) or flicking a ball with the index finger (flick; Fig. 1). We chose these 2 actions because finger configuration in the start phase of grasp actions was comparable with the end posture of flick actions, whereas the end posture of grasp actions was comparable with finger configuration in the start phase of flick actions. Thus, experimental stimuli may allow one to distinguish the corticospinal encoding of the finger aperture and the temporal phase of the observed action. We tested whether motor resonance is linked to the creation of an internal representation of finger configuration independently of the temporal phase of the observed action. Were this the case, maximal FDI facilitation should be obtained during observation of grasp-start postures and flick-end postures, where the index finger was maximally extended (Gangitano et al. 2001). In contrast, were motor resonance influenced by the anticipatory simulation of the deployment of actions in the future, corticospinal facilitation should be found during observation of start and middle postures of both grasp and flick actions, where the actions were still ongoing, but not during observation of end postures, where the actions were complete.

Because the index finger was maximally extended in the grasp-start postures and maximally flexed in the flick-start postures, maximal motor facilitation during observation of both grasp and flick start phases cannot be ascribed to mere reading out of finger kinematics. This result would, thus, support the view that mirror corticospinal facilitation is specific for the observation of postures representing ongoing, but incomplete actions, and largely independent of mere reading out of finger configuration.

2.2 Materials and Methods

Participants

Eighteen healthy individuals (7 women) aged 19--37 (mean 22.1 years) were recruited at the University of Udine for the action observation TMS experiment. Furthermore, 6 additional individuals (3 women) aged 24-33 (mean 27.7 years), who did not participate in the TMS experiment, were recruited at the University of Bologna for the action execution experiment. All participants were right handed according to a standard handedness inventory (Briggs and Nebes 1975). They had normal or corrected-to-normal visual acuity in both eyes and were naı ve as to the purposes of the experiment. Information about the experimental hypothesis was provided only after the experimental tests had been completed. Participants gave their written informed consent and received credits for their participation in the study. The procedures were approved by the Ethics Committee of the IRCCS Eugenio Medea and were in accordance with the ethical standards of the 1964 Declaration of Helsinki. None of the participants hadneurological, psychiatric, or other medical problems or any contraindication to TMS (Wassermann 1998). No discomfort or adverse effects during TMS were reported or noticed.

Stimuli

Stimuli were color pictures taken with a digital camera during the execution of right-hand precision grasp and flick actions by 4 male (aged 22--28 years) and 4 female (aged 23--29 years) models. Presenting 8 different hand stimuli allowed minimizing habituation and loss of attention. For each model, we selected 3 snapshots at the initial (start), intermediate (middle), and final (end) phases of the 2 action sequences (Fig. 1). Pictures were modified by means of the Adobe Photoshop software (Adobe Systems Incorporated, San Jose, CA). Pictures depicting the 6 different hand postures of the same model were matched for color, luminance, and viewing perspective. A total of 48 stimuli were created They were presented on a neutral background and subtended a 15.963 11.97region viewed from a distance of 100 cm.

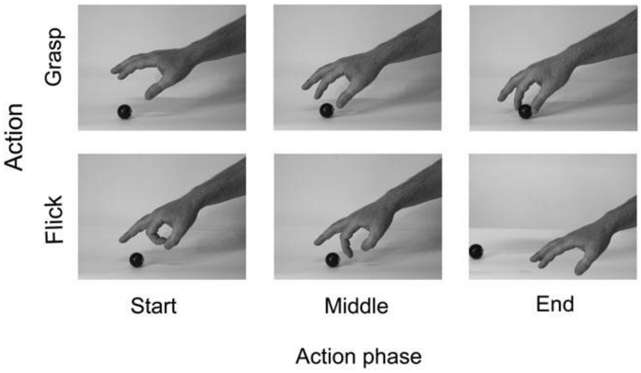


Figure 1. Examples of the experimental stimuli and factorial design. Participants viewed color pictures depicting the initial (start), intermediate (middle), and final (end) phases of 2 actions, namely, grasping a ball (grasp) and flicking a ball (flick). The crucial experimental manipulation was the finger configuration in the different phases of the 2 actions. Indeed, finger configuration in the start phase of grasp actions was comparable with the end posture of flick actions, whereas the end posture of grasp actions was similar to the finger configuration in the start phase of flick actions.

Electromyography (EMG) Recording and TMS

Motor-evoked potentials (MEPs) were recorded simultaneously from the FDI and abductor digiti minimi (ADM) muscles of the right hand. It is worth noting here that the FDI muscle is strongly involved in the execution of both grasp and flick actions; by contrast, the ADM muscle does not play a major role in the execution of either action. EMG recordings were performed through surface Ag/AgCl cup electrodes (1-cm diameter) placed in a belly-tendon montage. Responses were amplified, band-pass filtered (20 Hz to 2 kHz), and digitized by means of a Viking IV EMG equipment (Nicolet Biomedical, Madison, WI). The sampling rate of the EMG signal was 20 kHz. A prestimulus recording of 80 ms was used to check for the presence of EMG activity before the TMS pulse. To make sure there was no unwanted background EMG activity before the magnetic pulse, the signal from both muscles was additionally displayed in separate channels set at high sensitivity (50 lV). Moreover, during the preliminary session EMG signals were sent to loudspeakers to provide participants with an auditory feedback of their muscle relaxation. Focal TMS was performed by means of a 70-mm figure-of-8 stimulation coil (standard Magstim plastic-covered coil), connected to aMagstimRapid (TheMagstimCompany,Carmarthenshire, Wales), producing a maximum output of 2 T at the coil surface (pulse duration, 250 ls; rise time, 60 ls). The coilwas placed tangentially on the scalp,with the handle pointing backward and laterally 45 away from the midline, approximately perpendicular to the line of the central sulcus. This orientation induced a posterior--anterior current in the brain,which tends to activate corticospinal neurons indirectly via excitatory synaptic inputs (Di Lazzaro et al. 1998).We chose the above coil orientation based on the finding that the lowest motor threshold is achieved when the induced electric current in the brain is flowing approximately perpendicular to the central sulcus (Brasil-Neto et al. 1992; Mills et al. 1992). During the recording session, the coil was positioned over the left motor cortex in correspondence with the optimal scalp position (OSP), defined as the position from which MEPs with maximal amplitude were recorded. The OSP was detected by moving the intersection of the coil in 1-cm steps around the motor hand area of the left motor cortex and by delivering TMS pulses at constant intensity. Participants wore a tightly fitting bathing cap on which the scalp position for stimulation was marked. The coil was held by hand, and its position with respect to the mark was checked continuously to easily compensate for small movements of the participants' head during data collection. The resting motor threshold (rMT), defined as the lowest stimulus intensity able to evoke 5 of 10 MEPs with an amplitude of at least 50 lV, was determined by holding the stimulation coil over the OSP for the FDI muscle. Because we aimed to evaluate the differential modulation of MEPs recorded from the FDI muscle during observation of the different phases of actions, OSP and rMT were determined for the FDI. Thus, stimulation conditions were optimal to obtain facilitation of FDI MEPs in the less activating conditions, too. It is worth noting, however, that modulation of FDI, but not of ADM MEPs, was also obtained in previous studies (Urgesi, Candidi, et al. 2006; Urgesi, Moro, et al. 2006) where OSP and rMT were determined by using the ADM. Stimulation intensity during the recording sessions was 120% of the rMT and ranged from 48% to 86% (mean = 62.7%) of the maximum stimulator output. Using this procedure, a clear and stable signal was obtained from both the targeted muscles in all participants. The distance between the OSPs for the targeted muscles (FDI and ADM) turned out to be within the spatial resolution of the employed coil (ca. 1 cm; Krings et al. 1998). The MEP peak-to-peak amplitude (in mV) was collected and stored on a computer for offline analysis.

Procedure

Each participant was tested in a single experimental session lasting approximately 90 min. They sat in a comfortable armchair in a dimly lit room in front of a 15-in. monitor (resolution 1024 3 768 pixels; refresh frequency 60 Hz). They were instructed to keep their right hand on a pillow and to fully relax their muscles with the help of the auditory feedback coming from the loudspeakers. When muscular contractions were detected, stimulus presentation was suspended, and participants were invited to keep again full muscular relaxation. Before starting the recording session, participants were presented with examples of the stimuli and were informed that they were to be presented with static images depicting the start, middle, and end postures of precision grasp and flick actions performed by different male and female models. Subjects were also instructed to pay attention to the stimuli presented on the screen and were informed that, when requested at a given point during the experiment, they were to report the gender of the hand presented in the trial. The request was performed during 25% of trials according to a random selection procedure with the constraint of an equal distribution among the different conditions. The experimenter asked the participants to report the gender of the observed model at the end of the selected trials. However, no overt response was required at any time during stimuli presentation and MEP collection. The 6 types of pictures were randomly presented in 4 blocks of 24 trials. In each block, 4 stimuli per condition were presented with a random presentation of male and female models. A short rest was allowed before proceeding to a different block. Sixteen trials were presented for each of the 6 observation conditions (2 presentations for each of the 8 model hands), for a total of 96 trials. We also recorded 2 series of 8 MEPs while participants observed a white-colored fixation cross presented on a black background. One series was recorded at the beginning and the other at the end of the experimental session. Comparisons of MEP amplitudes in the 2 series allowed us to check for any corticospinal excitability change related to TMS per se. Stimulus presentation timing, EMG recording, and TMS triggering, as well as randomization of stimuli in a block, were controlled using E-prime V1.2 software (Psychology Software Tools Inc., Pittsburgh, PA) running on a PC. Stimuli remained on the screen for 1500 ms. On each trial, the magnetic pulse was randomly delivered between 500 and 16.7 ms before the offset of the stimulus to avoid any priming effects that could affect MEP size. A 9-s blank screen was presented before the next trial. Therefore, the interpulse interval ranged from 10 to 10.5 s. The choice of the interpulse interval was based on research by Chen et al. (1997) who showed that even 1 h of repetitive TMS at 0.1 Hz did not induce any change in corticospinal excitability. Thus, the procedure allowed us to rule out any experimental effect due to TMS per se. To ensure that all participants correctly discriminated between precision grasp and flick snapshots, an action discrimination task was administered at the end of the TMS session. The different start, middle, and end postures of the 2 actions were randomly presented on the computer monitor and participants had to indicate whether each image depicted a precision grasp or a flick action by pressing the left and the right button of the computer mouse, respectively. In keeping with the TMS session, stimulus duration was 1500 ms. Response accuracy was recorded and stored for automatic analysis. In a further post-TMS session, the experimental stimuli were presented in random order for 1500 ms on the computer monitor. For each picture, participants were asked to judge the perceived intensity of the implied motion by marking with the mouse cursor a vertical, 10-cm visual analog scale (VAS), where 0 cm was ‘‘no effect’’ and 10 cm was ‘‘maximal effect imaginable.’’ Two blocks were presented in a counterbalanced order in which participants were required to judge the intensity of the perception of the implied action of the hand or of the implied motion of the ball suggested by each of the 48 experimental stimuli.

Action Execution Experiment

To establish whether the corticospinal response to the observation of the different visual stimuli reflected mere read out of the level of muscle contraction rather than anticipatory coding of the observed actions, we recorded the EMG signals from the FDI and ADM muscles during actual execution of grasping and flicking actions. The participants of the action execution experiment stood in front of a table where an object with a similar size as that of the ball depicted in the experimental stimuli (2.5-cm diameter) was placed and fixed on a support. The object was connected to the computer and had a built-in button that was pressed during grasping and flicking movements, thus signaling the end phase of the movements. Movement execution was guided by a sequence of 2 different tones (3 and 2 kHz, respectively) that were generated by a computer (sinus waves: 150-ms duration, intertone interval: 1 s) and signaled the starting phase (go signal) and the end of the actions (corresponding to the end phase of the visual stimuli). Therefore, the grasping and flicking movements were performed with a 0.5-Hz frequency (following the 1-Hz pace of the metronome). Before proceeding to the EMG recording session, the participants of the action execution experiment were presented with the different experimental visual stimuli and were asked to repeatedly mimic the target action (grasp or flick) with their right hand. After a variable and self-paced number of repetitions of the target-mimed action, participants actually performed the target action by grasping or flicking the object with their right hand (and thus clicking the mouse button). This event generated a trigger signal that ceased the metronome for 2 s and was used to analyze the EMG activity. A block of 15 trials was recorded for each action (grasp, flick). The order of the blocks was counterbalanced across subjects. The EMG signals were recorded from the right FDI and the ADM muscle by means of a Biopac MP-150 (Biopac Corp., Goletta, CA) EMG equipment, band-pass filtered (20 Hz to 2 kHz, sampled at 20 kHz), digitized, and stored on a computer for offline analysis. Mean EMG responses were time locked to the finger--object contact (button press) and computed by averaging the root square rectified EMG signal across trials using 200-ms epochs over an interval of 1.2 s. The first 3 epochs covered the reaching component of the movements. Epochs 4 and 5 covered the grasping or flicking components and roughly corresponded to the start and middle phases of the visual stimuli. The last epoch included the 200-ms interval after button press and corresponded to the end phase of the visual stimuli.

Data Handling

Task compliance during action observation was good, as assessed by immediate verbal report of the gender of the presented hand. For each observation condition, we calculated the individual mean peak-to-peak amplitudes of MEPs recorded from the FDI and ADM muscles, the percentage of correct responses in the action discrimination task, and the mean VAS judgments of the perceived intensity of the implied hand action and of the implied object motion. Inspection of recognition performances in the action discrimination task revealed that 1 male and 1 female participant were below the chance level for pictures depicting the end posture of flick actions (0% and 38%, respectively). Because these 2 participants seemed to have systematically categorized stimuli depicting the flick-end postures as grasp action, their data were not included in the analysis. Thus, final analyses were based on data from 16 participants. Visual inspection of the EMG recordings confirmed full muscular relaxation in all participants during MEP recording. Trials with background EMG activity preceding the TMS pulse or with an MEP amplitude deviating more than 2 standard deviation (SD) from the mean for each observation condition were discarded (4.2% of the total).

No more than 3 MEPs for each observation condition were discarded and mean values were obtained from at least 13 MEPs per condition for each participant. A paired-sample t test (2-tailed) was used to compare the amplitude of MEPs recorded from the FDI and ADM muscles in the 2 series of fixation-cross trials presented at the beginning and at the end of the experimental session. The individual mean amplitude of MEPs recorded in the 2 fixation-cross series served as baseline. For each muscle, individual mean raw amplitudes of MEPs recorded during the 6 observation conditions were expressed as percentage of baseline values. Individual normalizedMEP amplitudeswere entered into a 23233 repeated-measure analysis of variance (ANOVA) with muscle (FDI, ADM), type of action (grasp, flick), and action phase (start, middle, and end) as within-subjects variables. The individual percentages of correct responses in the action discrimination task, the mean VAS judgments of the perceived intensity of the implied hand action and of the implied object motion were entered into separate 2 3 3 repeated-measures ANOVAs, with type of action and action phase as within-subjects variables. Furthermore, for each observation condition, we computed the Pearson correlation coefficients between the normalized FDI MEP amplitudes and 1) the VAS judgments of the perceived intensity of the implied hand action; 2) the VAS judgments of the perceived intensity of the implied object motion. Only the FDI MEP amplitudes were entered into the correlation analysis because ADM MEPs were not significantly modulated by any observation condition. The EMG signals recorded during action execution were analyzed by means of a 2 3 2 3 6 ANOVA with muscle (FDI, ADM), type of action (grasp, flick), and time (6 epochs) as within-subjects variables. All post hoc pairwise comparisons were carried out using the Newman--Keuls test. A significance threshold of P < 0.05 was set for all statistical tests.

2.3 Results

MEP Amplitude

Table 1 shows the mean raw MEP amplitudes recorded from the FDI and ADM muscles during the 2 baseline blocks and the 6 observation conditions. Mean raw MEP amplitudes during the 2 baseline blocks run at the beginning and at the end of the experimental session were not significantly different for either the FDI (t15 = 0.729, P = 0.478) or the ADM muscle (t15 = –0.06, P = 0.954). This indicates that TMS per se did not induce any changes in corticospinal excitability in our experimental session. To test whether mirror motor facilitation is higher during extrapolation of dynamic information about the upcoming action phases than the past ones, we compared normalized MEP amplitudes during observation of static snapshots depicting the start, middle, and end postures of grasp and flick actions (Fig. 2). The 3-way ANOVA yielded a significant main effect of muscle (F1,15 = 7.9, P = 0.013), with FDI normalized MEPs (mean ± standard error of the mean [SEM]: 103.92% ± 9.35%) being higher than ADM normalized MEPs (87.88% ± 7%). Thus, motor facilitation during observation of grasp and flick actions was higher for the FDI muscle, which is involved in the actual execution of the same movements.

Table 1
Amplitudes of MEPs recorded during baseline and observation conditions

	Baseline		Grasp			Flick		
	B1	B2	Start	Middle	End	Start	Middle	End
FDI	1.28 (±0.18)	1.19 (±0.19)	1.33 (±0.19)	1.3 (±0.17)	1.17 (±0.17)	1.41 (±0.22)	1.42 (±0.20)	1.28 (±0.19)
ADM	0.79 (±0.13)	0.79 (±0.18)	0.66 (±0.12)	0.67 (±0.14)	0.61 (±0.1)	0.73 (±0.17)	0.75 (±0.16)	0.75 (±0.15)

Table 1. Mean (±SEM) peak-to-peak amplitudes (in mV) of MEPs recorded from the FDI and ADM muscles during the 2 fixation-cross, baseline conditions run at the beginning (B1) and at the end (B2) of the experimental session, and during the 6 observation conditions.

The main effects of type of action (F1,15 < 1) and action phase (F2,30 = 2.19, P = 0.129) were non significant. Crucially, however, we found a significant interaction between muscle and action phase (F2,30 = 5.03, P = 0.013). Pairwise post hoc tests showed that MEPs recorded from the FDI (Fig. 2a) were more facilitated during observation of start (108.64% ± 9.62%) and middle postures (109.26% ± 11.28%) than during observation of end postures (93.85% ± 8.76%; $P < 0.001$ for both comparisons). Instead, comparable FDI MEPs were obtained during observation of start and middle postures ($P = 0.864$). Furthermore, no modulation during observation of the 3 phases of grasp and flick actions was obtained for MEPs recorded from the ADM (Fig. 2b; $P > 0.7$ for all comparisons), a muscle not involved in the actual execution of either actions. Although FDI MEPs were higher than ADM MEPs during observation of start ($P < 0.001$) and middle postures ($P < 0.001$), no between-muscle difference was obtained during observation of end postures ($P = 0.23$). The 2-way interactions between muscle and type of action ($F1,15 < 1$) and between type of action and action phase ($F1,15 < 1$) were nonsignificant.

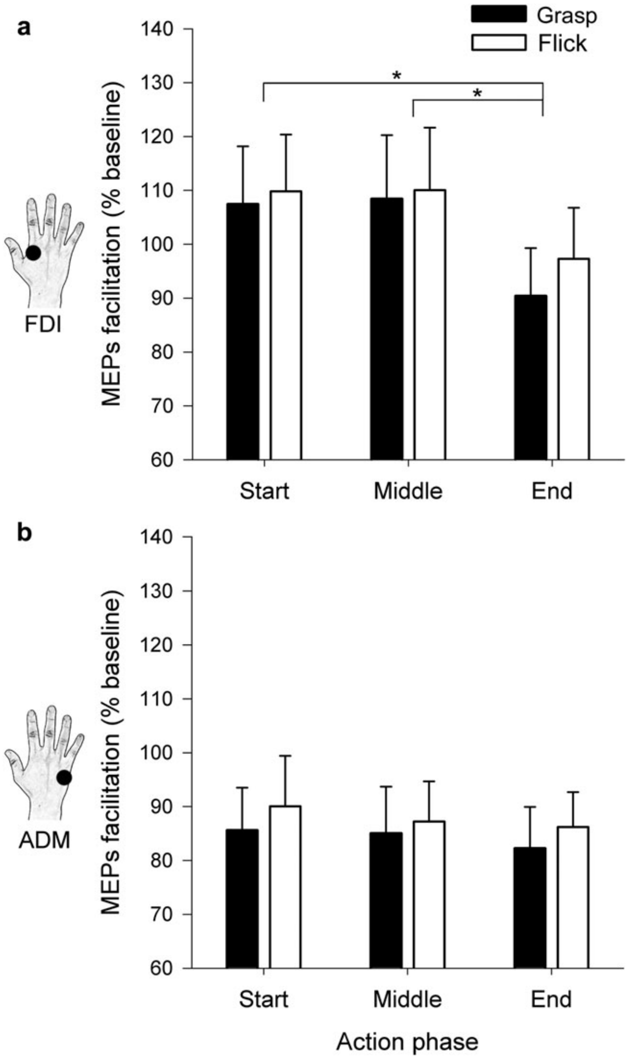


Figure 2. Muscular facilitation during observation of the different implied action phases. Amplitudes of MEPs recorded from the FDI (a) and ADM (b) muscles during the 6 observation conditions are expressed as value percentages of the MEPs recorded during the baseline (viewing a fixation cross). MEPs

facilitation was higher during the observation of the start and middle phases of the 2 actions with respect to their final postures. Error bars indicate SEM. *P\0.05.

Importantly, the nonsignificant effect of the 3-way interaction between muscle, type of action, and action phase (F2,30 < 1) showed that the greater motor facilitation during observation of start and middle postures versus end postures was independent of the finger configuration in the different phases of the 2 actions. Indeed, planned comparisons showed that FDI MEPs were lower during observation of grasp end postures than during observation of grasp start (F1,15 = 12.47, P = 0.003) and middle postures (F1,15 = 5.71, P = 0.03). In a similar vein, FDI MEPs were lower during observation of flick end postures than during observation of flick start (F1,15 = 4.81, P = 0.044) and middle postures (F1,15 =5.04, P = 0.04).

Action Discrimination

Action discrimination performance was above 90% for all observation conditions, suggesting that participants were able discriminate whether the static snapshot stimuli were taken from grasp or flick action sequences. The ANOVA on percent correct responses revealed a significant main effect of type of action (F1,15 = 6.95, P = 0.019), because responses for grasp snapshots (98.85% ± 0.46%) were more accurate than responses for flick action snapshots (94% ± 1.76%). Non-significant effects of action phase (F2,30 = 1.39, P = 0.265) and of the interaction between type of action and action phase (F2,30 = 2.6, P = 0.091) were found. Indeed, recognition performance was comparable between the 3 phases of grasp (start: 98.44% ± 1.22%; middle: 98.88% ± 0.6%; end: 99.25% ± 0.51%) and flick actions (start: 97.75% ± 0.75%; middle: 92.25% ± 3.03%; end: 92.38% ± 2.79%). This suggests that the difference between the motor facilitation during observation of start and middle postures and that obtained during observation of end postures cannot be ascribed to different abilities in recognizing the actions represented in the different pictures.

VAS Ratings Concerning Implied Motion of Each Stimulus

To test the relationship between motor facilitation and the perceived intensities of implied hand action and implied object motion, we compared VAS ratings on pictures representing the start, middle, and end postures of grasp and flick actions. The ANOVA on implied hand action VAS ratings (Fig. 3a)showed significant main effects of type of action (F1,15 = 4.86, P = 0.04), action phase (F2,30 = 9.89, P < 0.001), and their interaction (F2,30 = 7.47, P = 0.002). Post hoc tests showed that the subjective perception of implied hand action was higher for start than for middle (P = 0.021) and end (P < 0.001) grasp postures. Middle grasp postures suggested higher implied hand action perception than the corresponding end postures (P = 0.018).

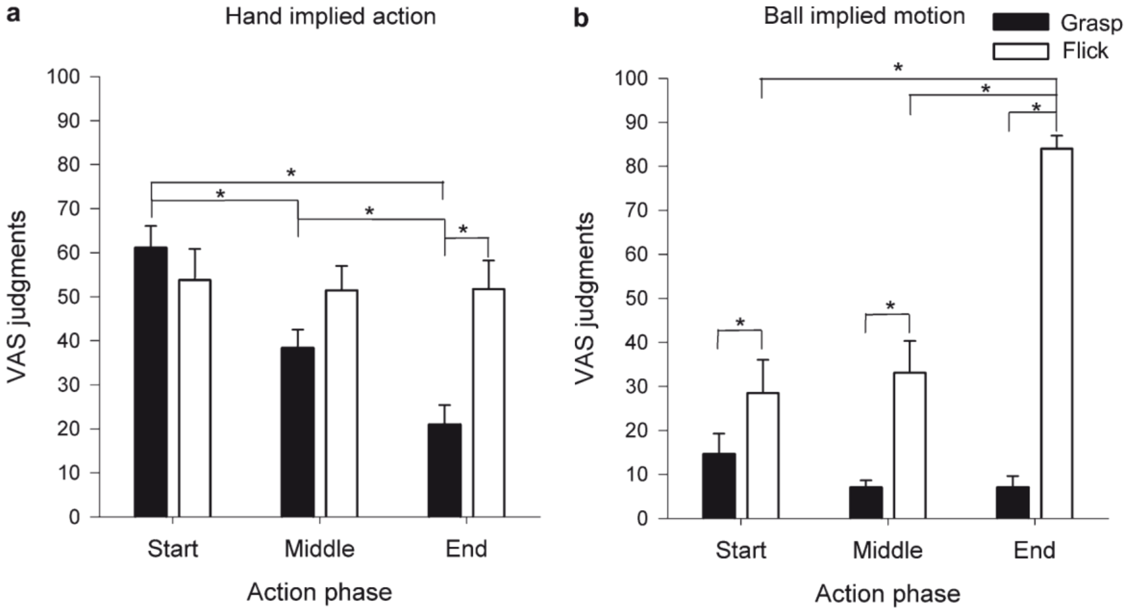


Figure 3. Subjective judgments of perceived intensity of the different implied hand actions and implied object motion. Mean VAS ratings on pictures representing the start, middle, and end postures of grasp and flick actions. (a) VAS ratings of the perceived intensity of the implied hand action were maximal for start and middle grasp postures, whereas no difference was observed between the 3 phases of flick actions. (b) VAS ratings on the perceived intensity of the implied object motion were higher for flick than for grasp action phases and were maximal for flick end postures, which exerted minimal facilitation on cortico-spinal excitability. Error bars indicate SEM. *P\0.05.

Thus, perception of implied hand action was maximal for the initial phases of grasp actions, which showed ongoing but incomplete movements. In contrast, no difference was observed between the perceived intensity of implied hand action suggested by the start, middle, and end postures of flick actions (P > 0.76 for all comparisons). Importantly, ratings of implied hand action perception for flick end postures were higher than ratings for grasp end postures (P < 0.001) and were not significantly different than ratings for grasp start postures (P = 0.38). Because grasp start postures activated the motor system to a greater extent than flick end postures, modulation of motor facilitation cannot be ascribed to different intensities of implied hand action perception for start, middle, and end postures. The ANOVA on VAS ratings of implied object motion (Fig. 3b) yielded significant effects of type of action (F1,15 = 55.78, P < 0.001), action phase (F2,30 = 27.23, P < 0.001), and their interaction (F2,30 = 41.86, P < 0.001). Post hoc tests showed that the subjective perception of implied object motion was higher for start, middle, and end flick postures than for start, middle, and end grasp postures (P < 0.015 for all comparisons). The ratings of implied object motion for the start, middle, and end postures of grasp actions did not differ from one another (P > 0.15 for all comparisons). In contrast, ratings of implied object motion perception were higher for the end postures than for the start (P < 0.001) and middle postures (P < 0.001) of flick actions. Thus, maximal perception of implied motion of the object was suggested by the end posture of flick actions. Because observing the end postures of flick actions did not activate the FDI motor representations, modulation of motor facilitation during observation of the different phases of grasp and flick actions cannot be ascribed to the perception of implied object motion. The absence of association between motor facilitation and implied motion perception was further corroborated by the analysis of the correlation between motor facilitation and implied motion perception ratings for each stimulus. Indeed, non significant correlations were found between the individual mean normalized FDI MEP amplitudes and the VAS ratings of implied hand action (all –0.35 < rs < 0.42, all Ps > 0.11) and implied object motion perception (all –0.39 < rs < 0.36, all Ps > 0.1).

Muscle Activation during Action Execution

The analysis of the mean root square EMG signal recorded during action execution (Fig. 4) revealed a significant main effect of muscle (F5,25 = 28.81, P = 0.003), accounted for by the higher EMG signal recorded in the FDI (0.123 ± 0.009 mV) with respect to the ADM muscle (0.080 ± 0.004 mV), a main effect of time (F5,25 = 50.66, P < 0.001) and,most importantly, a significant muscle 3 time interaction (F5,25 = 60.33, P < 0.001). The effect of the interaction was accounted for by the stronger increase over time of the EMG activity recorded from the FDI muscle in comparison to that recorded from the ADM muscle. The FDI EMG activity remained constant between the epochs 1 and 2 (P = 0.827) and between the epochs 2 and 3 (P = 0.211). Importantly, a significant increase was found between epoch 3 and epoch 4 (200--400 ms before the finger contacted the ball; P = 0.002). Maximum increase was found at epoch 5 (0--200 ms before the finger--object contact), corresponding to the flexion phase of grasping and to the extending phase of flicking, and epoch 6 (0--200 ms after the contact), corresponding to the end phase of the experimental visual stimuli. Crucially, the EMG signal during epochs 5 and 6 was comparable (P = 0.86) and was higher than that during all the previous epochs (all Ps < 0.001). A smaller but significant increase during epochs 5 and 6 was detected also in the ADM muscle (all Ps < 0.001), reflecting the postural adjustments of the hand during grasping or flicking with the index finger.

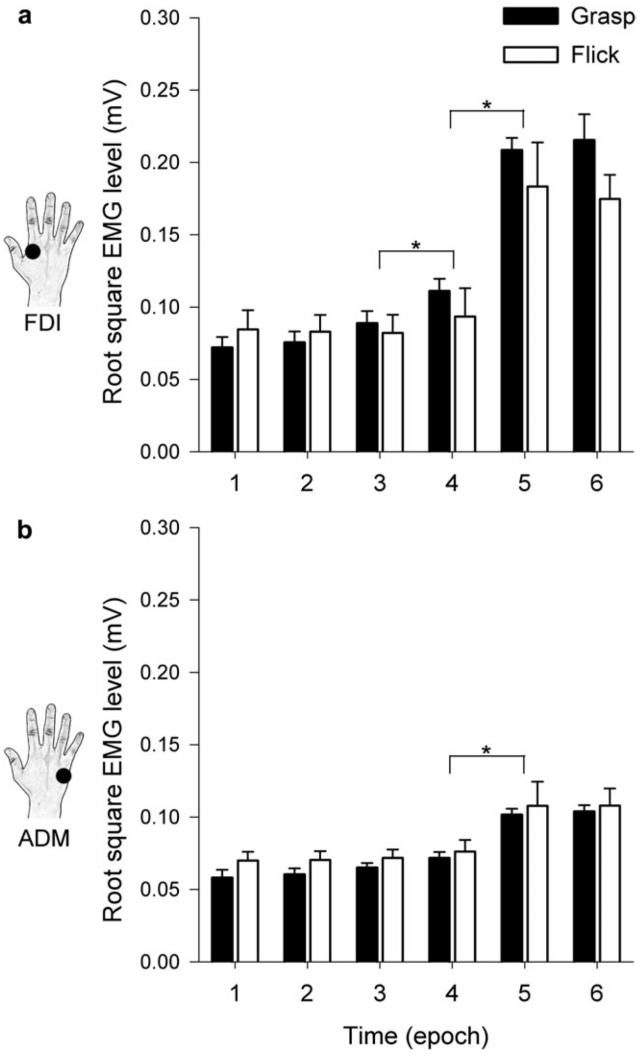


Figure 4. Time course of muscular activation during action execution. Mean root square EMG signals recorded from the FDI (a) and ADM (b) muscles during execution of grasp and flick actions. Results were

pooled across 6 epochs, each lasting 200 ms. The first 3 epochs covered the reaching component, whereas epochs 4 and 5 covered the grasping or flicking components of the movements, corresponding to the start and middle phases of the visual stimuli. The last epoch corresponded to the end phase of the visual stimuli. Error bars indicate SEM. *P\0.05.

The EMG signal during the epochs 5 and 6 was higher in the FDI than in all the epochs of the ADM muscle (all Ps < 0.001). No other significant main effect or interaction was found in the ANOVA (all Fs < 2.14, all Ps > 0.09), suggesting a similar time course of muscle activation during execution of grasp and flick actions.

2.4 Discussion

Somatotopic Mirror Motor Mapping of Implied Body Actions

Single-pulse TMS studies demonstrate that the mirror motor facilitation contingent on observation of dynamic displays of body actions (Strafella and Paus 2000; Gangitano et al. 2001; Borroni et al. 2005; Fadiga et al. 2005; Montagna et al. 2005; Romani et al. 2005; Urgesi Candidi, et al. 2006) specifically involves the muscles that would be recruited during the actual execution of the actions. In keeping with the only other TMS study (Urgesi, Moro, et al. 2006) on this issue, the present results show that, even in the absence of explicit dynamic information, cortical--spinal muscle representations are facilitated by the observation of static snapshots evoking the perception of implied actions. Moreover, we demonstrate that MEP modulation during observation of static photographs of pincer grasp and flick actions follows the same mapping rule of actual movements. Indeed, the MEP facilitation was selective for the FDI muscle, which is activated during actual execution of the observed actions. By contrast, no motor facilitation was observed for ADM, which has only a little role in the execution of the observed actions, mostly limited to postural adjustments of the hand. The motor facilitation during observation of implied body actions suggests that the human motor system is involved in the extrapolation of action information from static images of body postures. That mapping of implied actions is related also to motor regions is in keeping with a recent event related potential study that shows a specific cortical signature of observing implied action snapshots. This signature consists in a long-lasting positivity that was higher for the more dynamic stimuli, and its source was also in premotor and motor cortices and not only in cortical regions concerned with visual motion (e.g., V5/MT, EBA, or STS; Proverbio et al. 2009). Although single-pulse TMS cannot establish the specific cortical correlates of motor activations during action observation, mirror muscular facilitation seems to be linked to the activation of the frontal node of the mirror network that matches observed and performed actions (di Pellegrino et al. 1992; Rizzolatti and Craighero 2004). Neuroimaging studies demonstrate that the motor and premotor areas are activated by viewing dynamic full (Rizzolatti et al. 1996; Decety et al. 1997; Grafton et al. 1997; Iacoboni et al. 1999; Buccino et al. 2001; Costantini et al. 2005; Gazzola and Keysers 2009; Kilner et al. 2009) and point-light displays (Saygin et al. 2004) of body actions. Crucially, repetitive TMS of ventral premotor cortex disrupted motor facilitation during observation of biomechanically possible actions, but not impossible actions (Avenanti et al. 2007), thus hinting at the primary role of the ventral premotor cortex in mediating activation of the motor system during observation of actions that belong to the observer's motor repertoire. The ventral premotor cortex may be also involved in the perception of static images implying actions. A recent functional magnetic resonance imaging study in monkeys (Nelissen et al. 2005) has detected multiple representations of observed actions in the ventral premotor cortex, with patches activated only by full action displays and other patches activated also by mimicked actions or by static presentation of manipulable objects. In a similar vein, activation of human motor and premotor cortex was higher during observation of static pictures of goal-directed actions (Johnson-Frey et al. 2003), suggesting that mere observation of the action goal is enough to trigger mirror motor activation. However, by showing motor activation during observation of static snapshots of mimicked actions, we have demonstrated that the motor mapping of implied body actions is independent of the presentation of the target object (Urgesi, Moro, et al. 2006).

Furthermore, repetitive TMS of ventral premotor cortex impaired the visual discrimination of static images implying biomechanically possible body actions (Urgesi, Calvo-Merino, et al. 2007; Urgesi, Candidi, et al. 2007), but not impossible body actions (Candidi et al. 2008). Thus, the frontal node of the mirror motor system seems to play a crucial role in the discrimination of action information extrapolated from static body postures.

The involvement of motor representations in the perception of static body postures that imply action is also in keeping with the behavioral studies that have investigated the interferential effects exerted by the passive viewing of incongruent as compared with congruent actions on movement executions.

Indeed, the correct execution of an observer's actual movement can be influenced not only by viewing congruent or incongruent dynamic action sequences (Brass et al. 2000, 2001; Sturmer et al. 2000; Kilner et al. 2003), but also by single static frames suggesting congruent or incongruent actions (Craighero et al. 1996, 1999, 2002; Brass et al. 2000; Vogt et al. 2003). Thus, viewing a static image depicting moving bodies or body parts automatically activates action-related neural representations.

The Time Course of Motor Mirroring during Observation of Implied Actions

Studies indicate that the time course of motor activation triggered by action observation seems to parallel the dynamics of movement execution (Baldissera et al. 2001; Gangitano et al. 2001, 2004; Borroni et al. 2005; Montagna et al. 2005). In a previous single-pulse TMS study, the facilitation of the cortical representation of the FDI muscle during observation of reaching to grasp actions was maximal during presentation of the snapshots with maximal finger aperture, thus in the initial stages of the hand closing phase (Gangitano et al. 2001).

In a similar vein, a clear temporal modulation of amplitude of MEPs recorded from 2 hand muscles (flexor digitorum superficialis and FDI) was also found during observation of videos showing a hand reaching, grasping, and holding a sphere (Montagna et al. 2005). It is relevant that FDI facilitation was found not only during observation of the finger closing phase but also during observation of the hand closure and active object holding phase, that is, when the action was still ongoing (Montagna et al. 2005). By presenting in isolation static snapshots representing different phases of precision grasp movements (Urgesi, Moro, et al. 2006), we have previously found that facilitation of the FDI muscle responses was present during observation of the middle postures of a mimicked grasping action, when the hand had maximal grasp aperture. In contrast, FDI facilitation was absent not only during observation of a resting, relaxed hand but also during observation of a maximal finger closure hand, which suggests the movement has been completed. The temporal modulation of corticospinal excitability during actual and implied action observation is reminiscent of the firing properties of mirror neurons in the monkey's ventral premotor cortex, some of which discharge maximally during observation of the last phases of grasping (Umilta et al. 2001), others stop firing when the target object has been achieved, whereas others continue to discharge also during the active holding phase (Gallese et al. 1996). Previous studies, however, could not establish whether the temporal modulation of motor facilitation reflects the reading of finger configuration and muscular contractions in the different postures or the anticipatory simulation of future phases of the observed action.

Simulation of Implied Actions and Predictive Coding of Ongoing Actions

A main point of novelty of the present study is the maximal mirror motor facilitation during observation of start and middle postures of both hand grasp and flick actions. No facilitation was found during observation of end postures, which suggested that the movement was completed. Importantly, there was a great visual similarity between grasp start postures and end flick postures as well as between grasp end postures and flick start postures. Thus, the differential facilitation cannot be ascribed to the reading out of the finger kinematics at different hand apertures. It rather suggests that mirror motor mapping of implied actions is maximal for ongoing, but incomplete actions.

This effect may provide a specific neural basis for the forward bias in the recognition memory of moving conspecifics found in representational momentum experiments (Verfaillie and Daems 2002). Our results support and expand the notion that the functional role of motor activation during action perception is based on predictive coding. This process allows an onlooker to understand early the goal of actions and ultimately to read early the intentions of an actor (Blakemore and Frith 2005; Cattaneo et al. 2007; Kilner et al. 2007) as well as to anticipate the future phases of upcoming actions of others (Wilson and Knoblich 2005; Prinz 2006; Schubotz 2007; Schutz-Bosbach and Prinz 2007). In particular, Wilson and Knoblich (2005) have proposed that the motor representations activated during action observation may provide an internal model of the ongoing action by generating top-down expectations and predictions on its deployment in time. This model has 2 implications: 1) the observer's motor system generates predictive representations of others' actions by projecting the course of ongoing movements into the future; 2) predictions about others' actions are fed back into the visual system and exert top-down influence on action perception, thus allowing to complete missing information.

Our results provide compelling evidence for the involvement of mirroring processes in the anticipatory simulation of observed actions. It is worth noting that motor mirror neurons are activated also when the final part of an object grasp action cannot be seen but only inferred (Umilta et al. 2001). Therefore, motor mirroring may allow one to anticipate the course of ongoing actions and represent hidden information. In a similar vein, the facilitation of the human motor cortex during observation of grasping actions was suppressed by the artificial introduction of delayed aperture or sudden closure of fingers (Gangitano et al. 2004), suggesting that mirror mapping is affected by the predictability of the sequence of observed movements. Furthermore, motor activation in response to symbolic cues signaling an upcoming movement has been found in both adults (Kilner et al. 2004; Ramnani and Miall 2004) and children (Southgate et al. 2009). All in all, this evidence hints at the important role of the mirror system in predicting and anticipating the actions of other individuals. The higher motor facilitation during extrapolation of dynamic information about ongoing, but incomplete actions would suggest that motor mirroring may be inherently linked to predicting and anticipating the future behaviors of other individuals. The ability to provide predictive models of the perception of ongoing actions may rely on the previous motor knowledge of the observer. Several neuroimaging studies have shown that the activation of the mirror neuron system areas is modulated by the observer's motor experience (Calvo-Merino et al. 2005, 2006; Cross et al. 2006, 2009; Reithler et al. 2007; Orgs et al. 2008). On the other hand, the importance of motor expertise for action perception abilities has been demonstrated by behavioral investigations of elite athletes, who present superior abilities not only in the execution of complex actions but also in the prediction and anticipation of the behavior of other players (Farrow and Abernethy 2003; Abernethy and Zawi 2007; Abernethy et al. 2008; Weissensteiner et al. 2008). Crucially, the superior predictive abilities of elite basketball players with respect to naive and expert observers (e.g., coaches or sport journalists) were associated to differential motor activation during observation of the early phases of erroneous versus correct shots (Aglioti et al. 2008). Therefore, motor experience may endow the motor system with the ability to predict and anticipate the actions of others ahead of their realization.

The most novel result of the present study is that mirror motor facilitation is maximal during observation of implied action snapshot stimuli depicting ongoing but incomplete actions. In keeping with self- and other-action predictive coding models (Ramnani and Miall 2004), our study suggests that the frontal node of the observation--execution matching system is preferentially activated by the anticipatory simulation of the deployment of an action in the future. This would indicate that an important function of action mirroring processes is to derive from the observers’ motor knowledge specific predictions concerning the future implementation of others’ behaviors.

3 Study2 : Primary somatosensory cortex necessary for the perception of other people's action: a continuous theta-burst TMS experiment.

3.1 Introduction

When we observe somebody lifting a box we can readily judge if the load is heavy or light. Motor simulation, i.e. the recruitment of motor regions in perceiving the actions of others, has been suggested as a possible basis for such understanding (Rizzolatti and Sinigaglia, 2010). Transcranial magnetic stimulation (TMS) and lesion studies focusing on the motor system provide evidence that people become less accurate at perceiving certain aspects of the actions of others following a perturbation of inferior frontal cortex (IFC) and inferior parietal lobule (IPL) (Urgesi et al., 2007; Pazzaglia et al., 2008; Kalénine et al., 2010; Avenanti and Urgesi, 2011). In particular, Pobric and Hamilton (2006) found that TMS interference with IFC reduces participants' ability to judge the weight of a box when seen lifted.

On the other hand, mounting evidence suggests that the somatosensory cortices may also represent a key node of the action simulation network (Keysers et al., 2010) whose activity is strongly increased, for example, when seeing hands grasping objects (Pierno et al., 2009; Gazzola and Keysers, 2009; Caspers et al., 2010) or extreme joint stretching (Costantini et al., 2005; Avenanti et al., 2007). This suggests that somatosensory cortices may simulate somatosensory consequences of observed actions. In keeping, somatosensory regions are active when viewing others’ tactile or painful bodily states (Keysers et al., 2004; Bufalari et al., 2007; Lamm et al., 2010) and recently, Bolognini et al. (2011) have shown that primary somatosensory cortex (SI) TMS-perturbation makes people less accurate at judging whether a hand was touched or not.

When judging the weight of a box that we observe being lifted, we need not infer the presence or absence of touch, but must judge the motor effort exerted and/or the intensity of the proprioceptive and tactile feedback experienced by that person. Whether SI plays a critical role in this latter process remains poorly understood and is the focus of the present study. We used the paradigm developed by Pobric and Hamilton (2006) in four new experiments. Participants had to estimate the weight of a box, by observing it being lifted. The task was performed in two counterbalanced sessions carried out after active or sham continuous theta-burst (cTBS; Huang et al., 2005) over a target area. In the first three experiments we targeted SI to test its critical role in action understanding, and two neighboring regions, the motor and the superior parietal cortex, to test for spatial specificity. In the fourth experiment, we applied cTBS over SI before participants judged the weight of a bouncing ball, to test for SI specificity to action understanding. Our results extend those of Bolognini et al. (2011) by showing that SI does more than social detection of touch; and extend those of Pobric and Hamilton (2006) by showing that beyond IFC, S1 has a role in inferring proprioceptive qualities from action kinematics. This supports a functional interplay between motor and somatosensory regions/representations in action perception (Keysers et al., 2010).

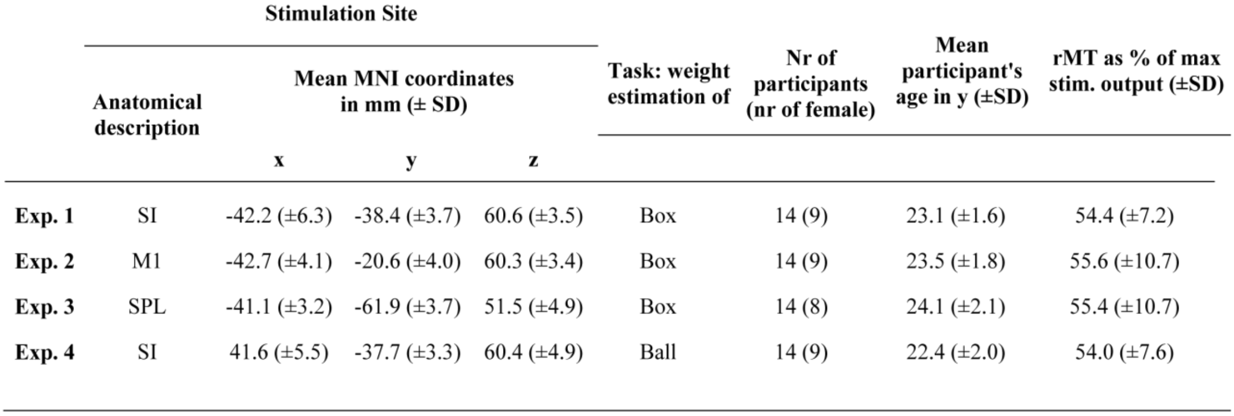
3.2 Materials and Methods

Participants

A total of 71 students from the University of Bologna took part in one of four TMS experiments (see Table 1 for the details) or in a psychophysical pilot study. All participants received course credit for their participation and provided written informed consent. All of them were right-handed with normal or corrected to normal vision. None of them had neurological, psychiatric, or other medical problems, or had any contraindication to TMS (Rossi et al., 2009). The protocol was approved by the local ethics committee at University of Bologna and was carried out in accordance with the ethical standards of the 1964 Declaration of Helsinki. No discomfort or adverse effects during TMS were reported or noticed.

TABLES

Table 1.



	Stimulation Site							
	Anatomical description	Mean MNI coordinates in mm (± SD)			Task: weight estimation of	Nr of participants (nr of female)	Mean participant's age in y (±SD)	rMT as % of max stim. output (±SD)
		x	y	z				
Exp. 1	SI	-42.2 (±6.3)	-38.4 (±3.7)	60.6 (±3.5)	Box	14 (9)	23.1 (±1.6)	54.4 (±7.2)
Exp. 2	M1	-42.7 (±4.1)	-20.6 (±4.0)	60.3 (±3.4)	Box	14 (9)	23.5 (±1.8)	55.6 (±10.7)
Exp. 3	SPL	-41.1 (±3.2)	-61.9 (±3.7)	51.5 (±4.9)	Box	14 (8)	24.1 (±2.1)	55.4 (±10.7)
Exp. 4	SI	41.6 (±5.5)	-37.7 (±3.3)	60.4 (±4.9)	Ball	14 (9)	22.4 (±2.0)	54.0 (±7.6)

Table 1. Task, stimulation site, and sample characteristics in the four TMS experiments.

Experimental design, tasks and procedure

All four experiments were composed of three parts: preparatory, active-cTBS, and sham-cTBS sessions. During the preparatory session the optimal scalp position and the resting motor threshold were evaluated by means of motor-evoked potentials (MEPs) recording (see Transcranial magnetic stimulation paragraph for more details). Once the target site was individuated, it was marked on the scalp and Talairach coordinates were estimated using the neuro-navigation system. The participant was then familiarized with the experimental task by performing a practice block of 60 trials. At the end of the practice, the participant rested for 10 minutes in front of the computer before continuing with the other two sessions. During the active-cTBS session the experimenter administered 40s of off-line continuous theta-burst stimulation over the target site, by placing the intersection of the coil tangentially to the scalp with the handle pointing backward and laterally at a 45˚ angle away from the midline. Two blocks of 30 trials (~5 min duration each) were performed at five and twelve minutes after the stimulation (Figure 1A). Between blocks and trials, participants were asked to rest. Active-cTBS is known to suppress the excitability and disrupt functions related to the target area for about 30-60 minutes (Huang et al., 2005; Franca et al., 2006; Bertini et al., 2010). Since the task was completed within 20 minutes after active-cTBS administration, performance should reflect the inhibitory influence of active-cTBS over the stimulated site. The sham-cTBS session was exactly the same as the active-cTBS session except that the coil was positioned, over the target site, perpendicular to the scalp.

The order of the active- and sham-cTBS sessions was counterbalanced across participants. Additionally, active- and sham-cTBS sessions were separated by 90 minutes to ensure that any inhibitory effects were carried over from one session to the other. During these 90 minutes participants were asked to remain relaxed and seated on a comfortable chair. Participants were randomly assigned to the different experiments. In experiments 1-3, participants watched 4.4s video-clips showing a hand lifting a small box and placing it on a shelf after receiving stimulation over the left SI, left M1 and left SPL respectively (see also Figure 1A). After each video, participants had to estimate the weight of the lifted box by answering the question "How heavy is the box?" by means of a 5 points scale, with 1 corresponding to the lightest and 5 to the heaviest weight estimation (Figure 1A). Five different movies, representing 5 different box weights were shown to the participants in a randomized order. Each movie was presented 12 times, 6 for each block (total number of movies per block = 30). In experiment 4, stimulation was delivered over the left SI and the movies of the box were replaced with video of a ball falling from the top of the screen to then bounce at the bottom until stop (no hand throwing the ball was visible; Figure 1A).

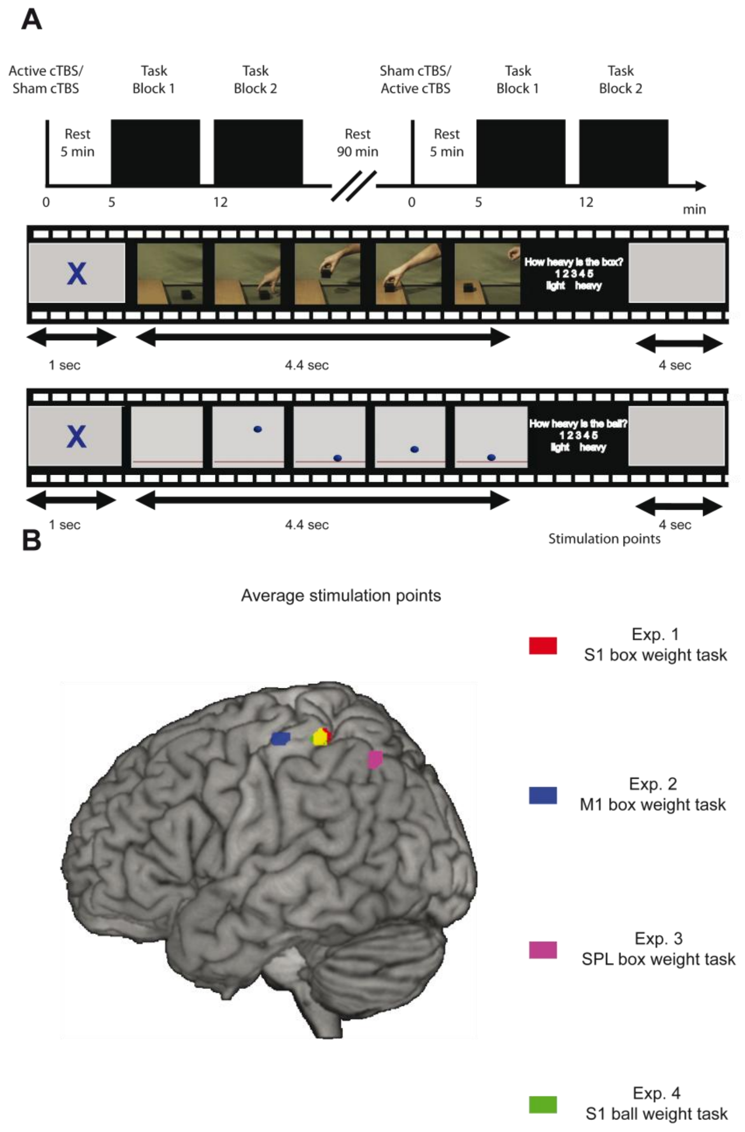


Figure 1. (A) Experimental design. (B) Average stimulation sites for experiments 1 to 4 (MNI coordinates).

The task consisted in judging the weight of the ball ("How heavy was the ball?"). As for the box there were 5 different movies representing 5 different ball weights. The number of trials was the same number of trials as in experiments 1-3.

In both tasks, each video was preceded by a 1 s fixation cross, and participants answered by pressing one of 5 keys with the left hand (ipsilateral to the stimulation site) to indicate a number from one to five. They were instructed to answer as quickly and accurately as possible. Participants wore headphones providing white noise thereby eliminating auditory information during task performance.

Visual stimuli and pilot study

All the video stimuli come from previous experiments (Pobric and Hamilton 2006; Hamilton et al., 2007). Briefly, the five different videos of the hand lifting a box (experiment 1-3) were generated by down sampling a single high-speed clip of a lifting hand to create the perception of 5 different box weights, ranging from approximately 50g to 850g. Since they all derive from the same video, they are very well controlled for visual differences not relevant for the task. The videos of the bouncing balls (experiment 4) were generated using Matlab (www.mathworks.com/) as in previous research (Pobric and Hamilton, 2006). Again a perception of 5 different weights was created by modifying two parameters which affect the elasticity of the ball and thus creates the perception of observing balls of different weights. All video clips were presented using custom-made software written in Matlab (www.mathworks.com/) at a resolution of 512x480 pixels and 30 frames per s on a 17 inch monitor.

A pilot study conducted on 12 participants (8 females, mean age 22.8 y ± 2.0) not participating to the TMS experiments was performed to check that accuracy in judging the weight of the ball was comparable to that of the box.

Two participants presented very low performance ($R2 < 0.2$; same procedure used in the TMS experiments, see data analysis) in both tests and were discarded. A t-test in the remaining sample confirmed that the performance was indeed comparable in the box (mean R2 ± s.e.m. = 0.46 ± 0.04) and ball (0.47 ± 0.04) weight estimation tasks ($t9 < 1$, $p = 0.93$)

Transcranial magnetic stimulation protocol

The cTBS protocol lasted 40 s and consisted of bursts of 3 TMS pulses delivered at 50 Hz, with each train burst repeated every 200 ms (5 Hz) for a total of 600 pulses (Huang et al., 2005). Stimulation was administered with a 70 mm figure-eight stimulation coil connected to a Magstim Rapid2 (The Magstim Company, Carmarthenshire, Wales, UK).

Previous studies have suggested that motor experience before or after the administration of cTBS may alter its effect on cortical excitability (Iezzi et al., 2008; Todd et al., 2009; Iezzi et al., 2011); thus, in all the experiments, before active-cTBS participants rested for at least 10 minutes. After active-cTBS, they rested for 5 minutes before running the task to allow the active-cTBS effect to reach its maximum level (Huang et al., 2005). To be consistent, the same rest periods were included in the sham-cTBS sessions.

Pulse intensity was set at 80% of the resting motor threshold (rMT) and was comparable in the four experiments (F3,52 = 0.10, P = 0.96; Table 1). In those participants with rMT > 64% of maximum stimulator output (2 participants in experiment 1 and 4, and 3 participants in experiment 2 and 3) the intensity was set at the maximum allowed by the stimulator (51%; on average this intensity corresponded to 76% ± 3 of rMT; Bertini et al., 2010). The rMT evaluation was performed by recording motor-evoked potentials (MEPs) induced by single-pulse TMS of the left motor cortex. MEPs were recorded from the right first dorsal interosseus (FDI) by means of a Biopac MP-150 electromyograph (Biopac Corp, Goletta, CA.). EMG signals were band-pass filtered (20 Hz-1.0 kHz, sampled at 5 kHz), digitized and displayed on a computer screen. Pairs of silver/silver chloride surface electrodes were placed over the muscle belly (active electrode) and over the associated joint of the FDI muscle (reference electrode). A ground electrode was placed on the ventral surface of the right wrist. The optimum scalp position (OSP) was chosen so as to produce maximum amplitude MEPs in the FDI muscle. The rMT was defined as the lowest level of stimulation able to induce MEPs of at least 50 µV with 50% probability (Rossini et al., 1994).

Target sites and neuro-navigation

Target sites on the scalp were identified based on functional-anatomical methods and then the Talairach coordinates corresponding to the projection of the target sites on the brain surface were estimated by means of a neuronavigator system (SofTaxic Navigator). Figure 1B illustrates the stimulation sites on a brain model. In experiment 1 and 4 scalp locations corresponding to the left SI was targeted by moving the coil 2.5 cm back with respect to the OSP (corresponding to the M1 hand area). TMS studies that successfully targeted the somatosensory hand area positioned the coil 1-4 cm posterior to the motor hotspot (Avenanti et al., 2007; Harris et al., 2002; Balslev et al., 2004; Merabet et al., 2004; Fiorio and Haggard, 2005). We therefore assumed that positioning the coil 2.5 cm from the previously marked optimal scalp position (OSP) for activation of the right FDI muscle would reduce the activity of SI with minimum effects on M1. To test this assumption directly, we checked that TMS pulses at 105% rMT with the coil in the above position did not elicit any detectable MEPs. Neurophysiological studies indicate that cTBS over SI reduces the amplitude of somatosensory evoked potentials, confirming the inhibitory disrupting effect of cTBS-SI on the somatosensory system (Ishikawa et al., 2007; Poreisz et al., 2008). Notably, TMS may modulate activity in remote interconnected regions however it can also reveal local functional properties of the underlying target brain region (O'Shea et al. 2007; Avenanti et al., 2012) and this holds true for TBS protocols (Stefan et al., 2008). For example, stimulation of SI induced changes not only in SI but also in nearby regions such as the motor cortex (M1) (Ishikawa et al., 2007; Mochizuki et al., 2007), however the TBS over SI but not over M1 modulated tactile perception (Ragert et al., 2008) and TBS over M1 but not over SI altered motor performance (Schabrun et al., 2008).

To test directly anatomical specificity, in experiments 2 and 3, we applied cTBS over two sites adjacent to SI: the primary motor cortex (M1) and the superior parietal lobule (SPL). In experiment 2, left M1 was stimulated by placing the coil over the OSP, corresponding to the scalp projection of motor cortex hand area (Rossini et al., 1994). In experiment 3, left SPL was stimulated by moving the coil 5 cm back with respect to the OSP (Balslev et al., 2004). Thus stimulation of M1 and SPL occurred 2.5 cm forward and backward to SI, respectively.

Brain surface Talairach coordinates corresponding to the stimulated sites in SI (experiments 1 and 4), M1 (experiment 2) or SPL (experiment 3) were identified on each participant's scalp with the SofTaxic Navigator system (Electro Medical Systems, Bologna, Italy) as in previous research (Avenanti et al., 2007; Bertini et al., 2010; Serino et al., 2011). Skull landmarks (nasion, inion, and two preauricular points) and about 100 points providing a uniform representation of the scalp were digitized by means of a Polaris Vicra digitizer (Northern Digital Inc, Ontario, Canada). Coordinates in Talairach space were automatically estimated by the SofTaxic Navigator from an MRI-constructed stereotaxic template and later transformed to the MNI space for better visualisation. For illustrative purpose, spherical rois of diameter 4 mm around the mean target point from each TMS experiment were created using Marsbar (Brett et al., 2002) running in MATLAB 7.5 (Mathworks Inc., Sherborn, MA, USA) and then overlaid on the MNI brain template from MRIcron (http://www.cabiatl.com/mricro/mricron/index.html; Table 1 and Figure 1B).

Data analysis

Data were processed off-line. Performance for each participant in each session (active-cTBS, sham-cTBS) was summarized by the R^2 of the linear regression between the correct responses and the participant’s judgments, which gives a single measure incorporating both accuracy and variability. Moreover, mean response times (RTs) for each session were computed. Responses with RT that deviated by more than two standard deviations from the individual mean RT in the particular session were excluded from the analysis (less than 5% of total). In the pilot study, two participants with inaccurate performance ($R^2<0.2$) were removed from data analysis. The same procedure was applied in the TMS experiments. In experiment 1, 3 and 4 we tested a total of 15 participants, however in each of these experiments one participant was excluded due to inaccurate performance ($R^2<0.2$; these participants are not listed in Table 1). R^2 and mean RT of the remaining participants (N = 14 in each experiment) were submitted to mixed-model ANOVAs with Experiment (experiments 1-4) as between participant factor and Session (active-cTBS, sham-cTBS) as within participants factor. An additional one-way repeated measure ANOVA was carried out on performance contrasts computed as the R^2 difference between sham-cTBS and active-cTBS session. Post-hoc analysis was carried out using Duncan test to correct for multiple comparisons.

3.3 Results

The Experiment x Session ANOVAs on raw R2revealed a significant interaction ($F_{3,52} = 3.50$, $p = 0.02$) but no main effect of Experiment ($F_{3,52} = 0.09$, $p = 0.97$) or Session ($F_{1,52} < 0.15$, $p = 0.70$; Figure 2A). Post-hoc analysis showed that in experiment 1 (box weight judgment, SI stimulation) R2 value was lower in the active-cTBS than in the sham-cTBS session ($p = 0.02$), indicating a reduction in participant's performance to estimate the weight of the box seen lifted only after suppression of SI. No difference between sessions was found in experiments 2-4 (all $p > 0.2$).

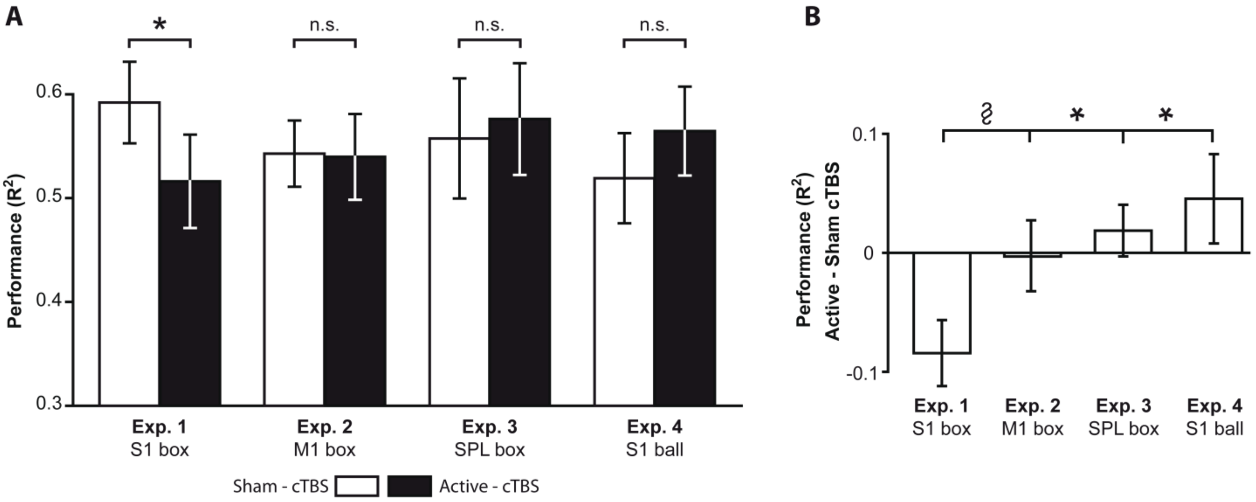


Figure 2. (A) Mean R2scores for the active-cTBS and sham-cTBS sessions in experiments 1 (SI box weight task), 2 (M1 box weight task), 3 (SPL box weight task) and 4(SI ball weight task). (B) Difference in R2 scores between the active-cTBS and sham-cTBS sessions in experiments 1 (SI box weight task), 2 (M1 box weight task), 3 (SPL box weight task) and 4(SI ball weight task).

The analysis of R2 difference (active-cTBS minus sham-cTBS; Figure 2B) computed in each experiment showed a lower index (worse performance after active-cTBS) in experiment 1 (box weight estimation, cTBS over left SI), than in experiment 3 (box weight estimation, cTBS over left SPL; p = 0.02) and experiment 4 (ball weight estimation, cTBS over left SI; p = 0.006). Moreover, the difference R2index in experiment 1 was marginally lower than in experiment 2 (box weight estimation, cTBS over left M1; p = 0.06). A comparison of the mean RTs between the sham- and active-cTBS in Experiment 1 revealed that responses after active-cTBS stimulation were on average 68 ms slower (Table 2), ruling out that lower accuracy in the box weight estimation after SI disruption was due to a speed-accuracy trade off. The Experiment x Session ANOVAs on mean RTs, however, did not show any main effect of Experiment (F3,52 = 0.05, p = 0.65) or Session (F1,52 = 0.78, p = 0.38; Table 2), nor their interaction (F3,52 = 0.63, p = 0.60; see Table 2). Thus, active-cTBS over SI selectively impaired accuracy in the weight estimation of observed lifted box, but did not affect speed of response.

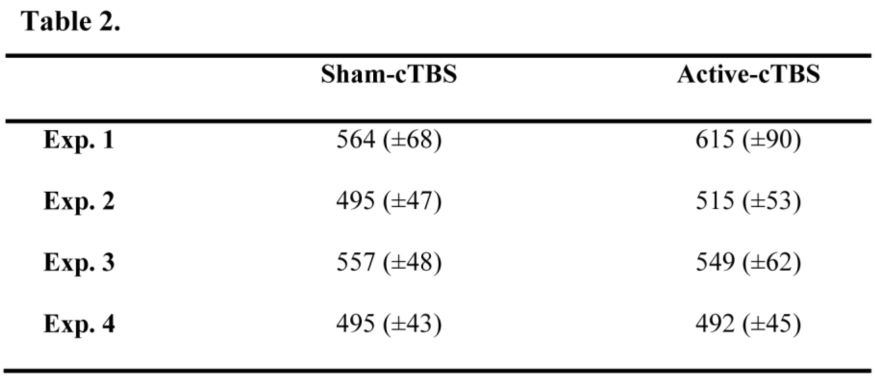


Table 2.

	Sham-cTBS	Active-cTBS
Exp. 1	564 (±68)	615 (±90)
Exp. 2	495 (±47)	515 (±53)
Exp. 3	557 (±48)	549 (±62)
Exp. 4	495 (±43)	492 (±45)

Table 2. Mean RTs (±SE) in ms from the four TMS experiments

3.4 Discussion

Our results show that, compared to sham stimulation, cTBS perturbation of SI selectively worsened participant's accuracy at estimating the weight of a box when seen lifted. In contrast, participants' performance remained comparable to sham stimulation when (i) participants judged the weight of a bouncing ball, and (ii) the stimulation was applied over the adjacent M1 and (iii) SPL. This suggests that SI is necessary for optimal weight estimation when a human agent is involved, and supports the idea that SI may enrich action understanding by providing vicarious representations of the proprioceptive consequences of the observed actions (Keysers et al., 2010).

So far only IFC and IPL have been shown to be necessary for action perception. TMS-disruption of IFC worsens participants' performance at judging the weight of a box when seen lifted (Pobric and Hamilton, 2006); and impairs visual discrimination of static images of actions with different kinematics (Urgesi et al., 2007) and correct recognition of deceptive movements (Tidoni et al. unpublished observations). Evidence for the role of the IFC in perceptual judgments of seen actions also comes from the TMS-adaptation (Cattaneo et al., 2010; Cattaneo et al., 2011) and TMS-priming (Cattaneo, 2010) paradigms developed by Cattaneo and colleagues. Additionally, patients with IFC lesion showed reduced performance in re-ordering pictures of human actions compared to physical events (Fazio et al., 2009), and were impaired in gesture comprehension (Pazzaglia et al., 2008; Saygin et al., 2004) and recognition of biological motion (Saygin, 2007). With regard to the IPL, lesions of this region impair recognition of transitive gesture (Kalénine et al., 2010; Buxbaum et al., 2005; Weiss et al., 2008) and of biological motion (Battelli et al., 2003). Finally, Tranel et al. (2003) showed that patients with lesions in both IFC and IPL were impaired in tasks involving action recognition from pictures. Although TBS may modulate activity in remote interconnected regions, this procotol reveals local functional properties of the stimulated areas (Stefan et al., 2008). If the effect of cTBS over SI were not the results of a perturbation of neurons in SI but, instead, of a spread of the effect of cTBS onto nearby premotor or parietal regions, known to be involved in action perception, one would expect that moving the coil forward or backwards would increase rather than decrease the detrimental effect on perception. This was not the case, supporting our claim that the effect was mediated by SI and that S1 itself contributes to action perception. However, we do not rule out that other regions, interconnected to SI (other than M1 or SPL), may have partially contributed to the observed effects. Many imaging and neurophysiological studies show that an entire network composed of ventral and dorsal premotor, anterior and posterior parietal cortices are activated in both action observation and execution (Pierno et al., 2009; Caspers et al., 2010; Avikainen et al., 2002; Rossi et al., 2002; Hasson et al., 2004; Caetano et al., 2007; Gazzola et al., 2007b; Gazzola et al., 2007a; Raos et al., 2007; Kilner et al., 2009; Turella et al., 2011; Arnstein et al., 2011). Of all these areas, the posterior sector of SI (BA2) that we stimulated in the current study is the region showing vicarious representation most consistently across participants (Gazzola and Keysers, 2009). Given the importance of both IFC (Pobric & Hamilton, 2006) and S1 (this paper) to action observation, as well as the exchange of information between these regions during action observation (Kokal and Keysers, 2010; Schippers and Keysers, 2011), it is relevant to consider what aspect of perception each region conveys. TMS studies show that seeing biomechanically possible and extremely overstretching movements facilitates the corticospinal representation of the muscles involved in the observed movements (Romani et al., 2005). Notably, rTMS over IFC disrupted motor facilitation during the observation of possible actions, while rTMS over SI disrupted the facilitation during observation of overstretching movements (Avenanti et al., 2007). The IFC could therefore provide vicarious motor representations derived from the kinematics that would enable the observer to produce a similar action, if the movement is biomechanically possible. SI, on the other side, could contribute to vicarious somatosensory (tactile and/or proprioceptive) action components, that emerge for instance during observation of overstretching finger movements. The contribution of SI in mapping somatosensory consequences of observed actions is supported by the findings that SI activity is increased when seeing other people grasping or manipulating objects (Keysers et al., 2010) or when seeing extreme joint stretching movements (Costantini et al., 2005). Evidence that somatosensory cortices are recruited both when sensing the body and during perception of others being touched or painfully stimulated (Valeriani et al., 2008; Keysers et al., 2010; Lamm et al., 2010), and that rTMS over SI impairs the ability to detect touch in others (Bolognini et al., 2011) further supports this interpretation.

While manipulation of biomechanical plausibility may dissociate somatosensory and motor components of action simulation, typically these two components are tightly interlinked. This is particularly evident when observing somebody else lifting objects. Recently, Alaerts et al. (2010) found that when participants observe an actor lifting objects of different weights, motor-evoked potentials are facilitated mainly by two factors: the kinematics of the movement and the degree of contraction of the hand. This facilitation could be the results of the integration in M1 of the observed kinematic information from IFC with proprioceptive/tactile information about hand-contraction from SI. The contribution of IFC, SI and other sensorimotor regions to perceiving the weight of objects seen to be lifted was suggested by previous studies showing that: i) lifting a box influences participant’s perceptual judgments of the weight of a box lifted by others (Hamilton et al., 2004); and, ii) the strength of this perceptual bias correlated with neural activity in a network of cortical regions including IFC, SI, M1 and SPL (Hamilton et al., 2006). However, these methods could not establish whether activity in SI was necessary for action perception. While previous evidence showed that IFC is necessary for correct performance in the box weight estimation task (Pobric and Hamilton, 2006), the present study provides further causative evidence that also SI, but not M1 or SPL, is critical for the social perception of weight. The lack of significant effect with M1 stimulation is not surprising. Although neural activity in this region may be modulated by action observation (Gazzola and Keysers, 2009; Nishitani and Hari, 2000; Fadiga et al., 2005; Scültz-Bosbach et al., 2009), it is likely that such activity plays no functional role for action perception. The activity may be a simple consequence of the strong reciprocal cortico-cortical connections, for example with IFC and/or SI (Geyer et al., 2000; Rizzolatti and Luppino, 2001). Similarly, previous TMS studies reported that M1 stimulation did not influence mirror-like motor facilitation (Avenanti et al., 2007) or perceptual judgments of seen actions (Cattaneo et al., 2011). The absence of effects after rTMS over SPL may be less expected. The SPL is a high-order multisensory region integrating visual and somatosensory information about limb position (Lloyd et al., 2002). Similarly to SI stimulation, direct stimulation of SPL (area 7) in awake neurosurgery patients produces sensations on the body but not motor output (Desmurget et al., 2009). Moreover, rTMS over this region may impair performance in proprioceptive tasks, although to a slightly less extent than rTMS over SI (Balslev et al., 2004). Although SPL is not classically considered as part of the mirror neuron system, studies show activation in SPL both during action execution and observation (Raos et al., 2007; Keysers and Gazzola, 2009). However, this region is less consistently activated relative to other sectors of the parietal cortex, such as the anterior intraparietal cortex or IPL (Van Overwalle and Baetens, 2009). It may be thus possible that SPL (and in particular area 7, the target of our study), plays a minor role in action perception, relative to nearby parietal regions, including SI and IPL that appears more critical for action perception. In conclusion, mounting evidence supports the claim that somatosensory cortices are activated not only during action execution, but also during perception of others' actions. Whether activation of SI is necessary to judge the actions of others remained unclear until now. Indirect evidence came from sensory neuropathy patients that lack a sense of touch on their own body. These patients showed impaired performance in a task requiring inference of another's expectation of a weight when seeing him lifting a box (Bosbach et al., 2005). Our findings, that cTBS over SI negatively influences the capacity to judge the weight of a box by observing the action (lifting) of other people, now provides direct evidence that SI is necessary for the optimal perception of at least certain aspects of other people's hand actions. Together with evidence that SI is also necessary for recognizing the facial expressions of others (Adolphs et al., 2000; Pitcher et al., 2008; Banissy et al., 2010), this suggests that SI seems to play a more important role in action perception than previously thought.

4 Study3 : Action simulation plays a critical role in deceptive action recognition

4.1 Introduction

Understanding others’ intentions is a key feature of social daily life. Interpersonal interactions may require one to accurately judge from non-verbal behavior if a person is honest or deceitful, and careful assessment of others’ bodily movements may be critical to detecting deceptive intentions (Runeson and Frykholm, 1983; Ekman and O’Sullivan, 1991; Vrij, 2004). However, the functional and neural mechanisms underlying the recognition of deceptive body movements (faked-actions, FAs) are poorly understood. FA recognition requires the reading of subtle action cues that violate observers’ predictions about the kinematics of the observed action (Bond et al., 1992; Frank and Ekman, 1997; Sebanz and Shiffrar, 2009), and thus it may involve comparisons with stored internal models of the observed action (Wolpert et al., 2003). Transcranial magnetic stimulation (TMS) offers the unique possibility to non-invasively stimulate the motor cortex and assess its activity by recording motor-evoked potentials (MEPs). Studies have shown that watching others’ actions increases the amplitude of MEPs recorded from those muscle that would be involved in the observed actions (Fadiga et al., 2005), suggesting that seeing actions triggers action resonance in the motor system. Notably, the motor system shows an anticipatory bias in the simulation of future phases of observed actions (Borroni et al., 2005; Urgesi et al., 2010), and it is modulated by watching erroneous actions (Aglioti et al., 2008). Thus, when seeing FAs, the detection of kinematic cues violating the predicted action may specifically modulate motor resonance processes. The inferior frontal cortex (IFC, including inferior frontal gyrus and ventral premotor cortex) represents a key region within the neural network mediating action simulation, i.e. the action observation network (AON; Avenanti and Urgesi, 2011). This region modulates action resonance processes (Avenanti et al., 2007, 2012b), is recruited when processing kinematic (Saygin et al., 2004; Majdandzic et al., 2009) and goal (Gazzola et al., 2007; Cattaneo et al., 2010) components of seen actions, and is sensitive to action intentionality (Iacoboni et al., 2005; de Lange et al., 2008). Notably, the only previous study exploring neural correlates of deceptive intentions recognition has shown that neural activity in IFC discriminates between FAs and truthful actions (TAs) (Grèzes et al., 2004); however, this IFC activation fell outside the classical AON. Moreover, a similar modulation was found in the temporo-parietal junction (TPJ), a region often associated with mental state attribution (Saxe and Powell, 2006; Frith and Frith, 2006). Critically, imaging cannot establish a direct causal link between brain and function, and to date no studies have tested whether the IFC (or TPJ) is necessary for recognition of FAs. Here, we provide correlational and causative evidence that action simulation is actively involved in such recognition. We recorded MEPs to single-pulse TMS to directly investigate whether observation of FAs modulates action resonance processes when performing a Faked-Action-Discrimination (FAD) task. Then, we tested the critical role of the AON sector of IFC (and of TPJ, as a control) in recognizing FAs and TAs, by using online repetitive TMS (rTMS) during performance of a FAD-task and a control task.

4.2 Materials and Methods

Participants. A total of 138 healthy subjects took part in the study. Sixty subjects (28 women, age range 19-27) participated in one of three TMS experiments, 10 subjects (6 woman, age range 24-39) participated in an action execution experiment, and 68 subjects (39 women, age range 20-35) were tested in one of four pilot studies. All the subjects were right-handed according to a standard handedness inventory (Briggs and Nebes, 1975), had normal or corrected-to-normal visual acuity in both eyes, and were naïve as to the purposes of the experiment. None of the participants had neurological, psychiatric, or other medical problems or any contraindication to TMS (Rossi et al., 2009). Participants provided written informed consent, and the procedures were approved by the ethics committee at the Department of Psychology and were in accordance with the ethical standards of the 1964 Declaration of Helsinki. No discomfort or adverse effects during TMS were reported or noticed.

General aims and study design. Studies of deception detection traditionally have focused on verbal communication. Nevertheless, people also commonly deceive others through nonverbal cues. Previous research has shown that intentions can be inferred from the ways in which people move their bodies (Ekman and O'Sullivan, 1991; Vrij, 2004; Bond et al., 1992; Frank and Ekman, 1997; Becchio et al., 2012). In the present study, we investigated the functional and neural mechanisms underlying recognition of deceptive body movements (FAs), i.e. movements in which the body is consciously used as an instrument for deception. We used a well established procedure in which an actor is asked to provide deceptive (FAs) or truthful (TAs) information regarding the action he/she is performing using his/her body movements only (Runeson and Frykholm, 1983; Grèzes et al., 2004). In particular, we asked actors to grasp, lift and place a cube that could be light or heavy and, in some cases (FAs), we instructed the actors to lift the cube as if it had a weight different from the actual weight. Thus, FAs were actions in which the actors pretended to lift a light cube as if it were a heavier one or to lift a heavy cube as if it were a lighter one. Conversely, TAs were actions in which the weight appearance that could be estimated by seeing the actor's movements reflected the cube's actual weight. In three main TMS experiments, participants were tested in a FAD-task, in which they saw actors lifting and placing a cube and had to judge whether the actor was providing deceptive (FAs) or truthful (TAs) information concerning the weight of the lifted cube. It should be noted that this task was not designed to explore deception recognition in general but to investigate the mechanisms underlying recognition of deceptive body movements, in particular deceptive hand movements.

In experiment 1, we used a correlational TMS approach and recorded MEPs to explore motor system activity during FAD-task performance. In experiment 2 and 3 we used a causative approach and investigated the effect of TMS-induced virtual lesions over IFC or TPJ on performance in the FAD-task and in a difficulty-matched control task that did not require participants to assess the presence of deceptive intents. Our findings suggest that action simulation activity in the motor system is sensitive to seen deceptive movements and is critical to visually discriminating between FAs and TAs.

Experiment 1: single-pulse TMS and EMG during action observation and execution.

Twenty five subjects were tested in the first experiment. Fifteen subjects (6 women, mean age 21.5 y, range 19-25 y) took part in a single-pulse TMS session aimed at exploring motor system modulation during active recognition of FAs and TAs video-clips. To allow investigation of motor resonance with a high degree of muscle specificity, in the present experiments we focused on FAs/TAs performed with the dominant hand, in contrast to the fMRI study of Grèzes and colleagues (2004) in which a FAD-task showing full body actions was used. In that study, discrimination of FAs/TAs modulated IFC and TPJ activity in the right hemisphere, in keeping with the notion that full body actions recruit right-lateralized action observation neural networks (Van Overwalle and Baetens, 2009). In contrast, evidence indicates that action simulation activity detected with single-pulse TMS is largely contralateral with respect to the observed effectors (Aziz-Zadeh et al., 2002; see also Shmuelof and Zohary, 2005; Gazzola and Keysers, 2009; Cabinio et al., 2010; for convergent imaging evidence). Thus, since our stimuli depicted a right hand, in experiment 1 we stimulated the left motor cortex and recorded MEPs from the right hand. Two muscles were considered: i) the first dorsal interosseous (FDI) which is directly involved in controlling the strength of the grip during lifting and placing and was found to be modulated by the object's weight during observation of lifting (Alaerts et al., 2010a; Senot et al., 2011); and, as control muscle, ii) the flexor carpi radialis (FCR), which was found not to be modulated by the object's weight during lifting observation and execution (Alaerts et al., 2010a, 2010b). To compare action observation with execution, the EMG activity from the right FDI and FCR muscles of 10 additional subjects (6 women, mean age 27.6 y, range 24-39 y) was recorded during the execution of the same actions depicted in the video-clips. Transcranial magnetic stimulation and electromyography recording during action observation. MEPs were recorded simultaneously from the right FDI and FCR by means of a Biopac MP-150 (BIOPAC, USA). EMG signals were band-pass filtered (30-500 Hz), digitized (sampling rate at 5 kHz) and stored on a computer for off-line analysis. Pairs of Ag-AgCl surface electrodes were placed in a belly-tendon montage on each muscle, with two further ground electrodes on the wrist and on the elbow. A figure-of-8 coil (70 mm diameter) connected to a Magstim Rapid2 stimulator (Magstim, Whitland, Dyfed, UK) was placed over the left motor cortex. The intersection of the coil was placed tangentially to the scalp with the handle pointing backward and laterally at a 45° angle away from the midline. This orientation induced a posterior-anterior current in the brain, which tends to activate corticospinal neurons indirectly via excitatory synaptic inputs (Di Lazzaro et al., 1998). The orientation was chosen based on the finding that the lowest motor threshold is achieved when the induced electric current in the brain is flowing approximately perpendicular to the central sulcus (Brasil-Neto et al., 1992; Mills et al., 1992). Participants wore a tightly fitting bathing cap on which the coil was moved over the left hemisphere to determine the FDI optimal scalp position (OSP). The OSP was then marked on the cap to ensure correct coil placement throughout the experiment. Stimulation intensity during the recording sessions was 120% of the resting motor threshold (rMT), defined as the lowest stimulus intensity able to evoke 5 out of 10 MEPs with an amplitude of at least 50μV (Rossini et al., 1994) in the higher threshold muscle, namely, the FCR. This way a stable signal could be recorded from both muscles. Participants' rMT ranged from 41% to 74% (mean ± s.e.m.: 58% ± 2.16) of the maximum stimulator output.

Stimuli and Task

A non-professional male actor was videotaped while reaching, grasping, lifting and placing a cube on a shelf with his right hand (see Figure 1). Two cubes with identical visual appearance (size: 5x5x5 cm) but different weight (50g, 650g) were used. During the first part of the recording session, the experimenter correctly informed the actor about the cube's weight (TA). In a second part of the recording, the experimenter correctly informed the actor about the cube's weight and instructed him to lift the cube as if it had a different weight (FA); that is, in some trials the actor pretended to lift the light (50g) cube as if it weighed 650g (apparently heavy weight), and in other trials he pretended to lift the heavier (650g) cube as if it weighed 50g (apparently light weight). Four types of videos were created following a 2 (weight appearance: light, heavy) x 2 (action type: TA, FA) design: apparently light TA, apparently heavy TA, apparently light FA, apparently light FA. For TAs, weight appearance reflected the cube's actual weight, while for FAs weight appearance provided deceptive information about the real weight. The clips were black and white videos of 5000 ms duration (30 fps) subtending 17.3 x 13.2 degrees of visual angle. We used B&W videos to prevent local changes in skin tone due to hand contraction from conveying information about the real weight of the cubes. Videos were carefully checked for the absence of local hand information. Moreover, kinematics analyses (see below) were carried out to ensure that movies contained subtle movement cues that could be used to detect actor's intent to deceive.

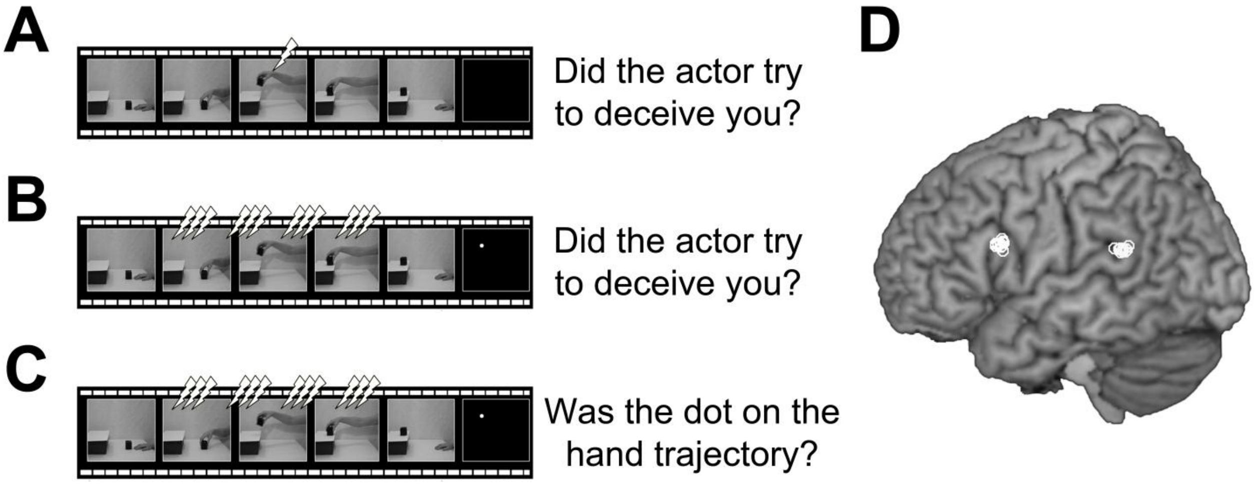


Figure 1. Timeline for the Faked-action-discrimination (FAD) task in experiment 1 (A), experiments 2 and 3 (B), and for the Spatial-control (SC) task in experiments 2 and 3 (C). IFC and TPJ stimulation sites (white circles) (D) reconstructed on a standard template using MRIcro (v1.40; http://www.mricro.com).

Two different versions of each visual stimulus type were used in the single-pulse TMS session, based on the result of a pilot psychophysical experiment performed on 25 subjects (19 females, mean age 25.88 y, range 20-33 y) not participating in the TMS study. This psychophysical experiment was aimed at selecting TA and FA clips that were recognized with ~75% accuracy among an initial sample of 60 clips. Thus a total of 8 different clips were presented in experiment 1. To maximize the probability that, during action observation, perceivers would access stored internal models of the observed actions, in a preliminary phase of experiment 1, participants were asked to lift the same two cubes used in the video-clips (about 20 times each, random presentation). Then they performed the FAD-task (Figure 1A): subjects were informed that they had to observe an actor lifting a cube, and that in some cases the actor lifted the cube as if it were heavier or lighter than its actual weight. Participants' task was to decide (forced choice) whether or not the actor was trying to deceive them concerning the cube's real weight. The experiment began with a practice block of 24 trials (3 presentation x 8 videos; accuracy ± s.e.m., 75% ± 2) during which responses were collected by keypress. During MEP recording, participants provided verbal responses ("Yes/No") only at the end of each video, while the experimental question was on the screen ("Did the actor try to deceive you?"). The very same procedure was used in the pilot psychophysical study except that all the responses were collected by keypress.

Procedure

Action observation. The experiment was programmed using custom software (developed in C#) to control the video-clip sequence and trigger TMS. Participants were tested in seven TMS blocks. The first and the last block (15 trials each) served as baseline: subjects kept their eyes closed with the instruction to imagine watching a sunset at the beach (Fourkas et al., 2008; Borgomaneri et al., 2012). In the remaining experimental blocks (32 trials each), participants were presented with the FAD-task. Each trial started with a gray screen (1000 ms duration) followed by the clip (5000 ms); during the clip a TMS pulse was delivered and MEPs from the FDI and FCR were recorded. For each trial, a TMS pulse was randomly delivered in the second half of the clip (covering the lifting and placing phase). The overall experimental design included a combination of 2 Muscle (FDI, FCR), 2 Action type (TA, FA) and 2 Apparent weight (light, heavy). Each video-clip was repeated 20 times, resulting in a total of 160 trials (equally) distributed across the 5 blocks (40 MEPs per condition and muscle). Video-clips were presented in a random order. In order to avoid changes in excitability due to verbal response (Tokimura et al., 1996; Meister et al., 2003), participants were invited to answer only at the end of each clip, a few seconds after the TMS pulse. After response, the screen appeared black for 4-6 sec. This way the inter-pulse interval was >10 sec, thereby avoiding changes in motor excitability due to TMS per se (Chen et al., 1997). This was directly confirmed by the lack of changes in MEP amplitude between the first (mean amplitude ± s.e.m.: FDI: 1.42mV ± 0.24; FCR: 0.42mV ± 0.09) and the last baseline block (FDI: 1.77mV ± 0.25, t13 = -1.53, p = 0.15; FCR: 0.55 mV ± 0.12, t13 = -1.57, p = 0.14). Action execution. To compare action observation with execution, ten additional subjects (not participating in the single-pulse TMS experiment) were asked to reach, grasp, lift and place a cube on a shelf with their right hand while EMG activity from the right FDI and FCR was recorded by means of the electromyograph. The very same cubes (size: 5x5x5; weight: 50gr, 650gr) and apparatus of the TMS session were used. Four types of actions were performed: apparently light TAs, apparently heavy TAs, apparently light FAs, and apparently light FAs. Each condition included 12 action execution trials that were performed in two separate blocks of 6 trials each. Thus, eight blocks were carried out, one for each movie of the TMS session. In each block, a brief practice phase was initially performed. During the practice phase participants were asked: i) to watch one of the movies depicting a FA/TA on a light/heavy cube (6 times); ii) to perform the observed action on the same cube (as shown in the movie) during online presentation of the clip (6 times). After this practice phase, subjects were asked to keep lifting the cube in that way (FA/TA) without any movie (12 times) and their EMG signal was recorded. In each trial, subjects placed the arm and hand in a resting position with their muscle relaxed. Online EMG signal was visually inspected to check muscle relaxation. Subjects performed the action after a go signal. A custom-made electrical circuit signaled when the cube was lifted from the initial position and placed on the final position. This procedure allowed assessment of action execution using the same temporal frame as that used for MEP recording during action observation.

Data handling

Kinematic parameters. Spatio-temporal (arm acceleration, duration), configurational (wrist angle, grip aperture) and spatial (arm vertical peak) kinematic parameters of the actor's right arm were extracted on a frame-by-frame analysis using a custom Matlab script (Matlab, Mathworks) and processed off-line. Maximal grip aperture before and while grasping the cube was measured as the distance between the tips of the thumb and of the index finger (measured in pixels and converted in cm). Arm vertical peak and arm acceleration was measured with reference to the position of dorsal aspect of the wrist (in cm). For grip aperture and arm vertical peak data, a factorial ANOVA with Action type (TA, FA) and Apparent weight (light, heavy) as between movies factors was performed. For the other kinematic parameters, we also considered the specific phase of the movement and distinguished between lift and place phases. The lifting phase lasted from the start of cube displacement to the wrist vertical peak. The placing phase lasted from arm vertical peak until the end of object displacement as the object was put on the shelf (Alaerts et., 2010b). Arm acceleration was measured with reference to the position of the dorsal aspect of the wrist. Movement duration (ms), arm acceleration (cm/sec) and wrist angle (degree) were entered into mixed-model ANOVAs with Action type (TA, FA), and Apparent weight (light, heavy) as between movies factors, and Phase (lift, place) as a within movies factor. In these and in all the following ANOVAs, post-hoc analysis was carried out by means of Newman-Keuls test. EMG during action execution. EMG data were processed off-line. For each trial, the root mean square of the rectified EMG signal was measured from lifting to placing. The root mean square of the rectified EMG signal in the 100 ms preceding each go signal was considered as baseline. The mean EMG signal for each condition was expressed as a percentage from the baseline (EMG ratios) and analyzed using a three-way repeated-measure ANOVA with Muscle (FDI, FCR), Action type (TA, FA) and Apparent weight (light, heavy) as within subjects factors. To ensure that any change in EMG level during execution was not due to changes in preceding muscle tone, a further Muscle x Action type x Apparent weight ANOVA was performed on baseline EMG level. MEPs during action observation. One subject was discarded due to technical failure in MEP recording. Neurophysiologic data were processed off-line. MEPs associated with erroneous responses (21%) were removed from the analysis; moreover, trials with an EMG background activity > 10μV in the 100ms interval prior to the TMS pulse were separately discarded for FDI (11%) and FCR (8%). This procedure left more than 24 MEPs per experimental condition, muscle and subject. The peak-to-peak mean MEP amplitude (in mV) in each experimental condition and baseline block was measured. To reduce skewness, a logarithmic transformation was applied to mean MEP amplitudes [Log(value+1)] and MEP ratios (% of baseline blocks) were computed for each experimental condition. MEP ratios were entered into a three-way repeated-measures Muscle x Action type x Apparent weight ANOVA. To ensure that any MEP modulation was not due to changes in EMG background, a similar Muscle x Action type x Apparent weight ANOVA was conducted on the root mean square of the rectified EMG signal recorded in the 100 ms preceding the TMS pulse.

Experiment 2 and 3: repetitive TMS during action observation.

To investigate the neural bases of FA recognition, in experiment 2 we used online rTMS and tested the role of IFC (IFC stimulation group: 15 subjects, 7 women, mean age 21.9 y, range 20-24 y) and TPJ (TPJ stimulation group: 15 subjects, 8 women, mean age 22.0 y, range 19-25 y) in FAD. An additional IFC group (15 participants; 7 women, mean age 21.8 y, range 20-27 y) was tested in experiment 3. In both the experiments, we tested the hypothesis that the anterior node of the AON is critical for FAD. Experiment

1 showed that our FAD-task modulated the left motor cortex, confirming the rationale for selecting the left hemisphere during processing of right hand actions (Aziz-Zadeh et al., 2002; Shmuelof and Zohary, 2005). Studies suggest that during action observation the left motor cortex is influenced by activity from the action observation sector of the left IFC (Avenanti et al., 2007, 2012b). This region is known to be active during action observation and execution (Buccino et al., 2004; Molnar-Szakacs et al., 2005; Costantini et al., 2005; Gazzola et al., 2007; Kilner et al., 2009) and interference with this area impairs visual discrimination of static pictures depicting different actions/body postures (Urgesi et al., 2007a, 2007b; Candidi et al., 2008). In view of this, in experiments 2 and 3 we used rTMS to stimulate the action simulation sector of the left IFC. To avoid unwanted effects of hemispheric differences, as an active control site, we stimulated the TPJ in the same hemisphere. Notably, the left TPJ is a key region of a neural network involved in mentalizing (Ciaramidaro et al., 2007). Left TPJ is not only recruited when reasoning about the mental states of others (Young et al., 2011; Saxe and Powell, 2006). This region is specifically active when reading others' intentions during lying judgments (Harada et al., 2009) and, critically, it is also necessary for correct mentalizing, since lesions in this region impair the ability to make inferences about others' beliefs and to read others' intentions and desires (Samson et al., 2004; Apperly et al., 2004; Chiavarino et al., 2010). Therefore, stimulation of the left TPJ appears to be the ideal control condition for stimulation of the left IFC and it allows a direct contrast between critical nodes of the Mentalizing network and AON in the recognition of FAs.

Stimuli and tasks. In experiments 2 and 3, participants underwent the same FAD-task used in experiment 1: they were presented with TAs and FAs and had to judge whether the actor was trying to deceive them about the cube's weight (Figure 1B). To augment stimulus variability for the behavioral test, we increased the number of recorded clips, weights and actors. Six non-professional actors were thus videotaped while reaching, grasping, lifting and placing a cube on a shelf. Three visually identical cubes (size: 5 x 5 x 5 cm) with different weights (50g, 350g or 650g) were used. Using the same procedure described for experiment 1, we created new TA and FA clips. Two experimenters initially selected 12 actions for each actor from a pool of about 100 clips. The selected actions consisted of 6 TAs and 6 FAs: TA stimuli included two different versions of light (50g), medium (350g) and heavy cubes (650g); FA stimuli included two apparently light FAs (350g and 650g cubes moved as if they were 50g), two apparently medium FAs (50g and 650g cubes moved as if they were 350g) and two apparently heavy FAs (50g and 350g cubes moved as if they were 650g). A preliminary analysis performed on the temporal duration of lifting and placing (the main kinematic parameter that was found to differentiate visual conditions in experiment 1) suggested that for each weight appearance, the two FA recordings were not different in terms of variability relative to the two correspondent TA recordings. However, movement duration of FAs was more variable than of TAs: this was because the pool of FAs included movements that represented an exaggeration of the correspondent TAs (for example apparently heavy FAs were slower than heavy TAs and apparently light FAs tended to be faster than light TAs; see also experiment 1). This suggests that recognition of FAs and TAs in the FAD-task may rely on the monitoring of spatio-temporal cues in the observed actions (see experiment 1 for analyses of additional kinematic parameters differentiating the two classes of action). The 72 clips (12 clips x 6 actors) were tested in a psychophysical experiment in which a group of 20 participants (10 females, mean age 22.2 y, range 20-30 y) performed a FAD-task. Based on their performance, we selected a total of 26 clips (13 TAs, 13 FAs) from three actors that were recognized with ~75% accuracy. In the final sample, for each actor, an equal number of TA and FA clips was shown. For the FAD-task, two types of response were scored as correct, namely, a “yes” response to FAs (hits) and a “no” response to TAs (correct rejection). Two types of response were scored as incorrect, namely, a “yes” response to TAs (false alarms) and a “no” response to FAs (misses). This procedure enabled us to determine task sensitivity (d’) and criterion (c) indices of the task signal detection method (Green and Swets, 1966).Kinematic analysis of movies in experiment 1 suggested that recognition of deceptive body movements mainly relied on the processing of spatio-temporal (e.g. acceleration, movement duration) and configurational (wrist angle) cues differentiating FAs and TAs. To evaluate the specific role of IFC and TPJ in extracting deceptive intents from spatio-temporal and configurational action cues, a Spatial control (SC) task not requiring such processing was designed. During the SC-task the same set of clips used for FAD-task were presented and subjects had to decide (forced choice) whether a white dot presented for 350 ms at the end of each clip was located inside or outside the trajectory covered by the hand during the action (Figure 1C). This task required participants to maintain a global visuo-spatial representation of the hand path without the necessity to attend to subtle changes in acceleration or posture/configuration which are critical to detecting deceptive movements. For the SC-task two types of response were scored as correct, namely, a “yes” response to dot-on-trajectory (hits) and a “no” response to dot-outside-trajectory (correct rejection). Two types of response were assigned as incorrect, namely, “yes” response to dot-outside-trajectory (false alarms), “no” response to dot-on-trajectory (misses). Indices of task sensitivity (d’) and criterion (c) were estimated for the SC. A further psychophysical study (16 subjects, 7 female, mean age 24.4 y, range 20-32 y) was run to assess performance in the two tasks. Subjects were able to discriminate TAs and FAs in the FAD-task (d' = 1.26) and to correctly respond to the SC-task (d' = 2.00). Performance in the SC-task appeared non-significantly higher than in the FAD-task (t15= 3.79; p = 0.07). In experiment 3 the SC-task was made more difficult by changing the position of the dot only in those trials of experiment 2 in which accuracy was 90-100%. This procedure was successful in matching the difficulty of the two tasks (see results section). Neuronavigation. Coil position was identified on each participant’s scalp with the SofTaxic Navigator system (Electro Medical Systems, Bologna, Italy) (Avenanti et al., 2012a; Urgesi et al., 2007a, 2007b; Bertini et al., 2010; Serino et al., 2011). Skull landmarks (nasion, inion, and two preauricular points) and about 100 points providing a uniform representation of the scalp were digitized by means of a Polaris Vicra digitizer (Northern Digital Inc, Ontario, Canada). Coordinates in Talairach space were automatically estimated by the SofTaxic Navigator from an MRI-constructed stereotaxic template (Figure 1D). The IFC scalp location that corresponded best to the pars opercularis of the left inferior frontal gyrus (at the border with the ventral premotor cortex) was identified by means of the SofTaxic Navigator system and marked with a pen. On the basis of previous fMRI (Buccino et al., 2004; Molnar-Szakacs et al., 2005; Costantini et al., 2005; Gazzola et al., 2007) and TMS studies (Urgesi et al., 2007a, 2007b; Candidi et al., 2008; Avenanti et al., 2007, 2012b) we targeted the left IFC at coordinates (mean ± s.e.m.): x = -57 ± 0.4; y = +13 ± 0.3 ; z = +24 ± 0.3 (experiment 2); and: x = -57 ± 0.2; y = +13 ± 0.2 ; z = +24 ± 0.1 (experiment 3). Previous studies have shown that this region is active during action execution and observation (Kilner et al., 2009) and may play a role in action perception (Cattaneo et al., 2010; Avenanti and Urgesi, 2011). As a control, in experiment 2 we targeted the scalp location that corresponded best to the TPJ at coordinates: $x = -63 \pm 0.2$; $y = -44 \pm 0.4$; $z = +22 \pm 0.2$. The coordinates were chosen based on the study by Grèzes et al., 2004 but, to avoid unwanted effects of hemispheric differences, we selected the site in the left hemisphere. Notably this region is active when reading others' intentions during lying judgments (Harada et al., 2009) and damage to it impairs the understanding of others' intentions (Chiavarino et al., 2010). Stimulation of IFC and TPJ may cause contraction of facial and temporalis muscle fascia, respectively. To rule out that any differential effect of IFC/TPJ stimulation on performance was simply due to any difference in peripheral sensations, we performed a TMS pilot study on 7 subjects (3 women, mean age 25.4 y, range 20-35) not participating in the main experiments. Each subjects received 2 trains of rTMS over the left IFC and over the left TPJ (randomized order) using the same coordinates and stimulation parameters as used in experiment 2-3. Subjects were asked to report the unpleasantness of the scalp sensation by using a 10-cm visual analogue scale with 0 cm indicating "no effect" and 10 cm "maximal effect imaginable". Ratings were low and comparable for the left IFC (2.37 ± 1.7) and left TPJ stimulations (1.83 ± 0.93; $t7 = 0.77$, $p = 0.47$). These findings suggest that peripheral sensations do not likely explain differential behavioral effect due to IFC/TPJ stimulation. Procedure. Experiments 2 and 3 were carried out using the same apparatus, instruments and software as used in experiment 1. Before starting the rTMS session, subjects underwent a practical training as described for experiment 1 (cube lifting). Then the OSP and the individual rMT of the right FDI were determined (Rossini et al., 1994). After neuronavigation, subjects were presented with task instruction and an example of the stimulus presentation timeline. Each subject performed the FAD- and SC-task in two separate rTMS sessions presented in a counterbalanced order and separated by a 20 minute break. For each task, 2 blocks of 13 active-rTMS trials and 2 blocks of 13 Sham-rTMS trials were performed following an ABBA counterbalanced order. Each trial started with a grey screen (1000 ms duration) followed by the clip (5000 ms). In both tasks (FAD, SC) a white dot at the end of each movie was presented for 350 ms followed by the response screen (FAD-task: "Did the actor try to deceive you?"; SC-task: "Was the dot on the hand trajectory?") that remained active until response by keypress ("Yes/No"). Then, a black screen appeared in the inter-trial interval (lasting 8-12 sec). In both experiments and tasks, participants were asked to respond as quickly and accurately as possible by keypress, using the index and middle fingers of the left hand (ipsilateral to the stimulation site). On each trial, a time-locked single train of 6 Hz rTMS (12 pulses, 2 sec) was delivered when the actor's hand touched the cube (Figure 1B,C). The rTMS train covered the entire lifting and placing phase of all clips. Pulse intensity was set at 90% of rMT. Values of rMT (mean ± s.e.m.) were comparable across the three groups (IFC exp 2: 58% ± 1.5; TPJ exp 2: 56 % ± 2.9; IFC exp 3: 61% ± 2.3; $F_{2,24} = 0.87$, $p = 0.42$).

Data Handling.

Behavioral data were processed offline. In experiment 2 and 3 and in the psychophysical studies, accuracy converted into a measure of sensitivity (MacMillan, Creelman, 1991) was measured for each task (FAD, SC) and rTMS condition (Active, Sham). Outliers with performance exceeding the sample mean ± 2 st.dev. were removed (1 subject from each group in experiment 2). In experiment 2, a mixed-model ANOVA was performed on d', c and response time (RT) with rTMS (Active, Sham) and Task (FAD, SC) as within-subjects factors, and Stimulation site (IFC,TPJ) as a between-subject factor. In experiment 3, a repeated measure ANOVA was performed with rTMS (Active, Sham) and Task (FAD, SC) as within-subjects factors.

4.3 Results

Experiment 1 Actor's arm kinematic pattern

Movement duration. The Action type x Apparent weight x Phase ANOVA on movement duration (expressed in ms) revealed a significant main effect of Phase ($F_{1,4} = 18.42$, $p = 0.012$), with longer duration for the lifting (mean duration ± s.e.m.: 610 ms ± 50) relative to the placing phase (320 ms ± 30), a significant main effect of Action type and of Apparent weight (all $F > 18.00$, $p < 0.01$) and, importantly, an interaction between the two ($F_{1,4} = 128.00$, $p < 0.001$; Figure 2A). Post-hoc analysis revealed a longer mean duration for apparently heavy TAs (490 ms ± 80) than for apparently light TAs (420 ms ± 40; $p = 0.001$); the duration of apparently heavy FA (580 ms ± 160) was significantly longer than that of apparently heavy TAs ($p < 0.001$), while the duration of apparently light FAs (380 ms ± 60) was shorter than that of apparently light TAs ($p = 0.007$). No other significant interactions were found (all $F < 2.17$, $p > 0.22$).

Wrist acceleration. The Action type x Apparent weight x Phase ANOVA on mean acceleration (in cm/sec) of the wrist revealed non-significant main effects of Apparent weight and of Action type ($F < 5.54$, $p > 0.078$), and a significant Action type x Apparent weight interaction ($F_{1,4} = 10.94$, $p = 0.03$; Figure 2B) with greater acceleration for apparently light FAs (204.37 cm/sec ± 12.35) relative to the other three conditions (all < 142.41 cm/sec ± 14.70; all comparisons $p < 0.046$). No other significant main effects or interactions were found (all $F < 1.67$, $p > 0.26$). An additional Action type x Apparent weight ANOVA performed on wrist acceleration peak (in cm/sec) revealed a marginally significant main effect of Apparent weight ($F_{1,4} = 6.49$, $p = 0.06$) with greater acceleration peak for apparently light actions (353.83 cm/sec ± 33.65) relative to apparently heavy actions (296.77 cm/sec ± 18.74; Figure 2C). No other main effects or interactions were found (all $F < 4.83$, $p > 0.09$).

Grip aperture. The Action type x Apparent weight ANOVA on maximal grip aperture during the reaching phase (in cm) showed no significant main effects or interaction (all $F < 8.57$, $p > 0.21$; mean aperture across videos: 9.04 cm ± 0.31). Similarly, the Action type x Apparent weight ANOVA on grip aperture during the lifting/placing phases (in cm) revealed no significant main effects or interactions (all $F < 0.34$, $p > 0.66$; mean aperture across videos: 6.17 cm ± 0.03).

Arm vertical peak. The Action type x Apparent weight ANOVA on arm vertical peak (in cm) revealed only the main effect of Action type ($F_{1,1} = 13.79$, $p = 0.02$; Figure 2D) with higher arm peak height during TAs (27.70 cm ± 0.52) relative to FAs (25.94 cm ± 0.28). No other significant main effects or interactions were found (all $F < 2.87$, $p > 0.16$).

Wrist Angle. The Action type x Apparent weight x Phase ANOVA on wrist angle degree (in°) revealed only the main effect of Action type ($F_{1,1} = 18.55$, $p = 0.01$; Figure 2E) with greater wrist angle during FAs (168.46° ± 1.27) relative to TAs (162.01° ± 3.93). No other significant main effects or interactions were found (all $F < 3.77$, $p > 0.12$).

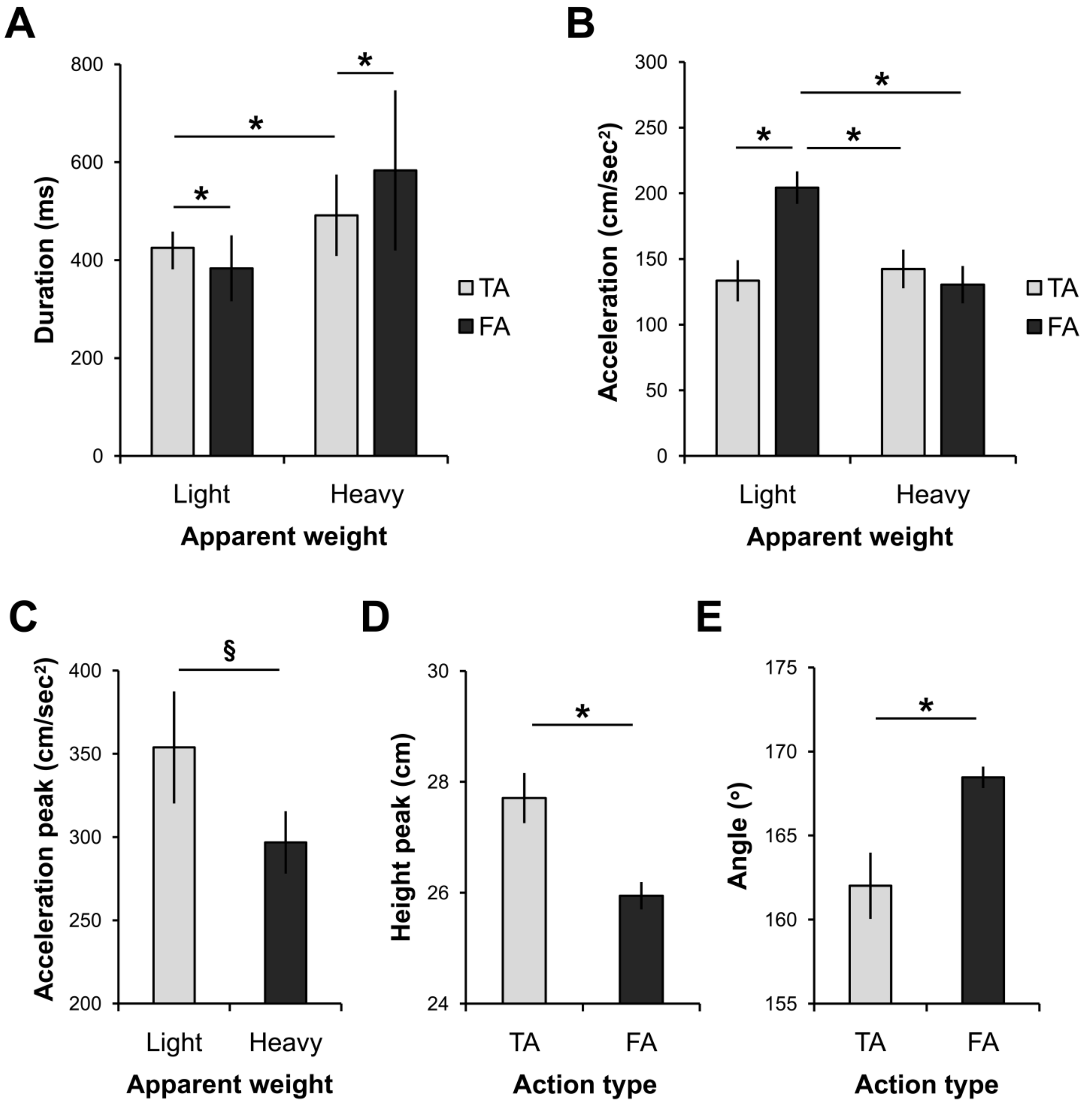


Figure 2. Kinematic parameters of the movements performed by the actor in the FAD movies. Movement duration (A); Mean wrist acceleration (B); wrist acceleration peak (C); wrist vertical peak (D); wrist angle (E). Asterisks indicate significant comparisons ($p < 0.05$). The § symbol indicates marginally significant comparisons ($p = 0.06$). Error bars denote s.e.m.

In sum, kinematic data suggest that during FAs the actor effectively/successfully modulated the acceleration peak of his arm in order to deceive the observer. However, the total duration of the FAs was exaggerated relative to that of the correspondent TAs (Brault et al., 2012): lifting and placing in the apparently heavy FAs (i.e. light cube moved as if it was a heavy cube) lasted longer than in the heavy TAs; whereas movements were faster in the apparently light FAs than in the light TAs. As a result, movement duration in the FAs was more variable than in the TAs and in principle observers could monitor such spatio-temporal information to solve the FAD-task. Moreover, mean acceleration of the wrist for apparently light (but actually heavy) cubes was greater than for all the other visual conditions both during lifting and placing. In addition, the arm vertical peak was lower and the wrist angle was greater during FAs relative to TAs. Thus, the actor’s intention to deceive affected spatio-temporal (mean arm acceleration/duration of lifting and placing) and configurational (max wrist angle) but also spatial (arm vertical peak) features of the performed action, and observers could rely on these subtle visual cues to accurately detect the intent to deceive. In contrast, the findings that grip aperture before or during lifting/placing phases was not different in the different conditions and the fact that videos were checked for the absence of changes in skin tone due to hand contraction, suggest that local information about the hand could not be used to perform the FAD-task.

EMG activity during action execution.

EMG during execution. Overall, during action execution, the EMG signal increased +207% with respect to the baseline levels. The Muscle x Apparent Weight x Action Type ANOVA performed on EMG ratios revealed a significant main effect of Action Type (F1,9 = 9.35, p = 0.014), a significant Action Type x Apparent Weight interaction (F1,9 = 28.49, p < 0.001) and, importantly, a significant three-way interaction (F1,9 = 9.05, p = 0.015). To further analyze this interaction, two separate Action type x Apparent weight ANOVAs were carried out, one for each muscle. The ANOVA performed on the FDI (Figure 3A) showed no main effect of Apparent Weight (F1,9 = 0.03, p = 0.86), a significant main effect of Action type (F1,9 = 32.92, p < 0.001) and, importantly, a significant two-way interaction (F1,9 = 33.42, p < 0.001). This interaction was entirely driven by the effect of the real weight of the cube: indeed, higher EMG level was found for the two conditions in which a heavy cube was lifted (TA, apparently heavy: 207% ± 14; and FA, apparently light: 236% ± 12) relative to the two conditions in which a light cube was lifted (TA, apparently light: 148% ± 5; and FA, apparently heavy: 171% ± 17; all comparisons p < 0.043). Both the former (p = 0.09) and the latter (p = 0.15) two conditions did not differ from one another. The ANOVA performed on the FCR (Figure 3B) revealed a non-significant main effect of

Apparent Weight (F1,9 = 1.12, p = 0.32), a marginally significant main effect of Action type (F1,9 = 4.43, p = 0.065) and, importantly, a significant two-way interaction (F1,9 = 19.43, p = 0.002). Higher EMG level was found when heavy objects were lifted as if they were light objects (apparently light FA: 271% ± 26) relative to the other three conditions (all < 218% ± 21; p < 0.006) which in turn did not differ from one another (all p > 0.18).

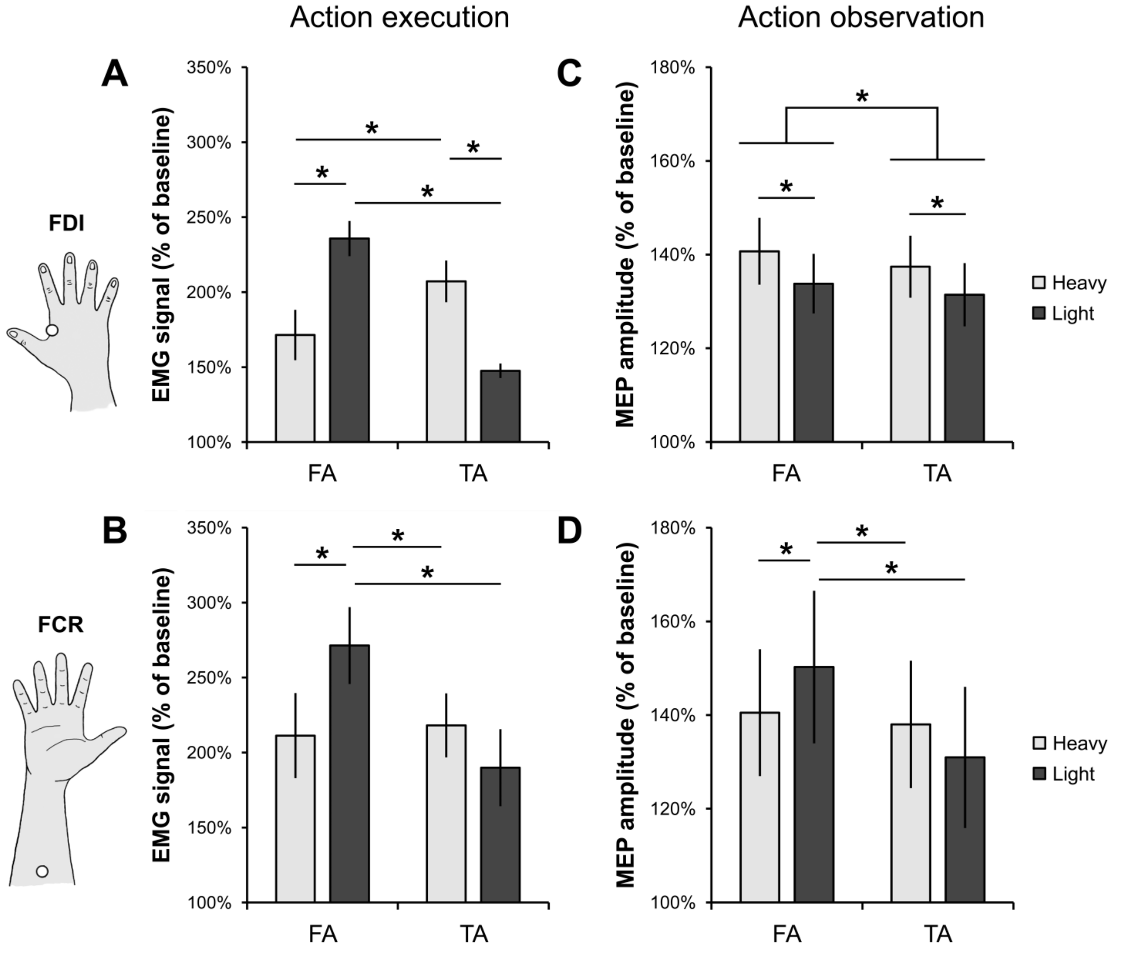


Figure 3. Results from experiment 1. Left panels show EMG activity recorded from the FDI (A) and the FCR (B) muscles during action execution. Right panels show MEP amplitudes recorded from the FDI (C) and the FCR (D) muscles during action observation. Light and dark gray columns indicate lifting actions with apparently heavy and light weight cubes respectively. During action execution, activity in the FDI muscle (A) was driven by the real weight of the object: greater EMG level was found for heavy (apparently heavy TA; apparently light FA) relative to light cubes (apparently light TA; apparently heavy FA). Activity in the FCR muscle was enhanced when a heavy weight was moved as if it were a light weight (B). During action observation, MEPs recorded from the FDI muscle were greater for apparently heavy than light weight and for faked- (FA) relative to truthful-actions (TA) (A). MEPs recorded from the

FCR muscle were greater when observing apparently light FAs relative to the other conditions (B). Asterisks indicate significant comparison ($p < 0.05$). Error bars denote s.e.m.

EMG background level. A further Muscle x Action type x Apparent weight ANOVA was performed on background EMG activity in the 100 ms preceding the go signal. The ANOVA showed a non-significant main effect of muscle ($F_{1,9} = 3.59$, $p = 0.09$; FDI: 0.093mV ± 0.002; FCR: 0.082mV ± 0.006), suggesting that during baseline participants slightly preactivated the FDI muscle which is critically involved in grasping. Note that this slight contraction during baseline may have underestimated the FDI signal increase during lifting and placing execution (represented as a percentage of baseline in Figure 3A) relative to the FCR muscle. However, no other main effects or interactions approached significance (all $F < 2.44$, $p > 0.15$). Thus, the differential pattern of FDI and FCR EMG activity during execution of the different types of motor acts cannot be ascribed to changes in the muscle tension preceding action execution. In sum, EMG recording revealed that the two muscles differentially contributed to the execution of the different action conditions. The FDI muscle was modulated by the real weight of the cube more than the specific action type, in keeping with the evidence that hand muscles are critically involved in modulating grip force during lifting (Alaerts et al., 2010a; Senot et al., 2011). In contrast, the FCR was not modulated by the real weight of the cube during TAs, in line with the notion that FCR is less directly involved in modulating arm force during ‘normal’ (TA) lifting and placing actions (at least when using weights <2.1 kg as in Alaerts et al., 2010a, 2010b). The FCR showed increased activity only in the apparently light FAs, reflecting the greater wrist effort and/or postural adjustment associated with lifting a heavy cube as if it were a light cube.

Observers’ motor reactivity to actor’s actions.

MEPs data. Overall, during the FAD-task MEP amplitudes increased +138% with respect to the baseline level. The Muscle x Action type x Apparent weight ANOVA performed on MEP ratios revealed a main effect of Action type ($F_{1,13} = 17.96$, $p < 0.001$), a Muscle x Action type interaction ($F_{1,13} = 9.37$, $p < 0.001$), and, importantly, a significant three-way interaction ($F_{1,13} = 9.03$, $p = 0.01$). To further analyze this interaction, two separate Action type x Apparent weight ANOVAs were carried out, one for each muscle. The ANOVA performed on the FDI muscle (Figure 3C) revealed a main effect of Apparent weight (F1,13 = 6.22, $p = 0.03$) with greater amplitudes during the observation of apparently heavy (139% ± 6) relative to apparently light weights (132% ± 6). This finding is in keeping with the evidence that observing heavier objects being lifted increases the excitability of the FDI muscle that is directly involved in the observed action (Alaerts et al., 2010a; Senot et al., 2011). The ANOVA also showed a main effect of Action type (F1,13 = 5.88, $p = 0.03$) with greater MEPs recorded during FAs (137% ± 6) relative to TAs (134% ± 6). No interaction between factors was found (F1,13 = 0.07, $p = 0.79$). The ANOVA performed on FCR (Figure 3D) showed no main effect of Apparent weight (F1,13 = 0.13, $p = 0.72$) but a main effect of Action type (F1,13 = 16.13, $p = 0.001$) and, importantly, a significant Action type x Apparent weight interaction (F1,13 = 7.01, $p = 0.02$). MEPs were greater during observation of heavy objects being lifted as if they were light objects (apparently light FA: 150% ± 16) relative to the other three conditions (all < 141%± 14; $p < 0.05$) which in turn did not differ from one another ($p > 0.12$).

EMG background level. To check whether the observed changes in corticospinal excitability during the FAD-task were due to any change in muscle tension, a Muscle x Action type x Apparent weight ANOVA was performed on background EMG activity in the 100 ms preceding the TMS pulse. The ANOVA did not show any significant main effects or interactions (Fs < 2.74, ps > 0.12; mean EMG signal: 0.026mV ± 0.001). In sum, experiment 1 shows a differential contribution of muscles controlling the hand (FDI) and the wrist (FCR) when lifting and placing objects and, importantly, it highlights the specific involvement of the cortical representation of the two muscles in the simulation of observed FAs/TAs. During execution, the FDI critically contributed to the control of grip force, with a specific modulation as a function of the actual weight of the cube. By contrast, the FCR was not modulated by the different weights during TAs. However, there was an increase in the FCR activity when a heavy cube was moved as if it were a light cube (apparently light FAs), reflecting the greater wrist involvement during this effortful action. It should be noted that during action observation there were no apparent local visual cues on the hand signaling the actual involvement of the FDI muscle in the different visual conditions. Indeed, kinematic analysis shows that grip aperture (which is controlled by hand muscles, including the FDI) was similar in all the movies. Moreover, no local information about hand muscles contraction (e.g. changes in skin tones) was present in the different videos. Thus, since heavy and light cubes were also visually identical, during observation, any involvement of the FDI muscle had to be inferred on the basis of global movement parameters (e.g. movement duration). Kinematic analysis suggests that accurate inference of the actual FDI involvement (grip force) required monitoring of the observed actions for their entire duration and integration of both configurational and spatio-temporal cues. On the other hand, kinematic and EMG data suggest that the greater acceleration of the wrist when a heavy cube was moved as if it were a light cube (apparently light FA) could have signaled the greater FCR involvement early. This may suggest that during observation FCR MEPs would reflect actual muscle involvement more accurately than FDI MEPs. Indeed, MEP data show greater FCR facilitation when observing apparently light FAs, thus closely resembling the modulation of the FCR muscle found during action execution. In contrast, FDI MEPs during action observation did not parallel action execution data. We found that watching apparently light and heavy objects being lifted differentially modulated the excitability of the observers' FDI muscle (Alaerts et al., 2010a; Senot et al., 2011), with greater "resonant" facilitations for apparently heavy than for apparently light objects. Thus, during observation, the cortical motor representation of the FDI muscle was affected by the apparent grip force that could be inferred on the basis of a rough categorization of the observed movement as quick (light weight) or slow (heavy weight). Critically, the hand motor representation was also sensitive to the type of actions being observed. Greater motor excitability was detected in the FDI muscle when watching FAs relative to TAs, indicating that recognition of deceptive movements enhanced the FDI resonant facilitation. These findings can be interpreted within the framework of predictive theories of action perception (Wilson and Knoblich, 2005; Kilner et al., 2007; Kilner, 2011; Schültz-Bosbach and Prinz, 2007; Kokal and Keysers, 2010; Schippers and Keysers, 2011; Avenanti et al., 2012b) according to which understanding of others' actions is mediated by the generative and predictive functions of the AON (Kilner et al., 2004; Avenanti et al., 2009; Urgesi et al., 2010). According to this perspective, during action observation the motor system starts generating a prior expectation about the observed action (e.g. its goal/intention and the associated motor commands). Given this prior, the AON generates a prediction about the sensory consequences of the action (i.e. its expected kinematics). This prediction is then compared with the actual sensory information and prediction errors arising from that comparisons are returned to the higher level to adjust the initial prediction (Kilner, 2011; Press et al., 2011). On the basis of this framework, we posit that during the FAD-task, changes in motor excitability reflected a weighted combination of priors generated in the motor system and prediction error signals returning to the motor system. The pattern of FCR and FDI MEPs can be promptly accounted for within this framework. After motor training with the cubes and visual exposure to the actor's movies in the initial phases of the task, participants may have learned that actions starting with larger mean wrist acceleration (apparently light FAs) are likely to use the FCR muscle to a greater extent and would result in more observed wrist movement. Hence, during the MEP recording phase of the FAD-task, seeing actions starting with larger wrist acceleration may have generated the prediction of a greater FCR involvement which was reflected in an increased excitability of the FCR motor representation. In these conditions, the AON would predict greater observed wrist involvement (Kilner, 2011; Press et al., 2011). Because of the close correspondence between the predicted (prior) and the observed actions, it is likely that excitability of the FCR muscle reflected mainly the prior and little prediction error. This may explain the similarity between MEPs during action observation and EMG during action execution. For the FDI muscle, the MEPs did not correspond so closely to the EMG data, likely because kinematic cues signaling the possible involvement of the index finger were more ambiguous in the initial phases of the movement. It is plausible that changes in FDI MEPs reflected both aspects of the prior prediction and the prediction error. When observing TAs, changes in FDI excitability (greater MEP for heavy than for light TAs) mainly reflected the prior (greater index finger involvement for heavy than for light cubes) and little prediction error. When seeing FAs, changes in FDI excitability reflected the (inaccurate) prior that was likely based on initial kinematic cues. As soon as sensory information violating the expected kinematics was available, a (facilitatory) prediction error signal arising from that comparison returned to the motor system and affected the cortical representation of the FDI, leading to a further increase in FDI motor excitability. This error signal may have been used to adjust the prior and recognize the deceptive intent in the actor. These findings indicate that: i) violation of predicted actions specifically modulates motor resonance processes with a high degree of muscle specificity; and ii) different sectors of the motor system dynamically map kinematic features of observed actions, with differential coding for apparently light and heavy weight lifting, and for FAs and TAs.

4.4 Experiment 2

Results from experiment 1 confirms the notion that watching right hand actions increases the excitability of the observer's left motor cortex (Fadiga et al., 1995; Aziz-Zadeh et al., 2002; Schütz-Bosbach et al., 2009; Borgomaneri et al., 2012), an effect that is likely mediated by activity in the left IFC (Avenanti et al., 2007, 2012b; Koch et al., 2010; Catmur et al., 2010), the human homologue region of the monkey ventral premotor cortex where mirror neurons have been discovered (di Pellegrino et al., 1992; Gallese et al, 1996). We found that observers' corticospinal system was sensitive to the apparent weight of observed objects being lifted (that is predicted on the basis of internal models of action) (Alaerts et al., 2010a, 2010b; Senot et al., 2011) and conveyed information about the possible violation of the predicted action (during FAs). These findings clearly demonstrate that FAD specifically affects action simulation in the motor system. However, they do not establish whether the AON is also necessary for performing FAD. To test whether the AON plays an essential role in visual recognition of FAs and TAs, a second experiment was carried out using online rTMS during the execution of the FAD-task. The AON was targeted in its anterior node, namely the left IFC and as an active control site we stimulated a key region within the Mentalizing network, namely the left TPJ. This way we contrasted the possible involvement of simulative (in IFC) and mentalizing (in TPJ) processing in FAD. Notably, experiment 1 suggested that spatio-temporal (e.g. acceleration) and configurational (wrist angle) features of seen actions are critical to discriminating FAs and TAs and thus recognition of deceptive intents may require monitoring of such action cues. To check for unspecific effects of rTMS, we tested participants in a SC-task that required monitoring of spatial features of seen actions (hand trajectory), but not to read others' intentions based on spatio-temporal/configurational cues.

The Task x rTMS x Stimulation site ANOVA performed on the index of sensitivity (d') revealed a main effect of Task ($F_{1,26} = 56.76$, $p < 0.001$) accounted for by higher accuracy in the SC (mean d' ± s.e.m.: 1.73 ± 0.46) than in the FAD-task (0.81 ± 0.21).

Importantly, a significant three-way interaction was found (F1,26 = 5.25, p = 0.03). To further analyze this interaction two separate rTMS x Stimulation site ANOVAs were carried out, one for each task. The ANOVA performed on d' computed from FAD-task performance showed a significant two-way interaction (F1,26 = 7.52, p = 0.01; Figure 4). Post-hoc analysis indicates that the interaction was accounted for by lower sensitivity in the IFC group during active-rTMS (0.51 ± 0.13) in comparison to sham-rTMS (0.97 ± 0.26; p = 0.03) and active-rTMS in the TPJ group (0.99 ± 0.26; p = 0.04). No change in performance was found in the TPJ group (p = 0.45). The rTMS x Stimulation site ANOVA performed on d' computed from SC-task performance showed no main effects or interactions (all F < 0.73, p > 0.40).

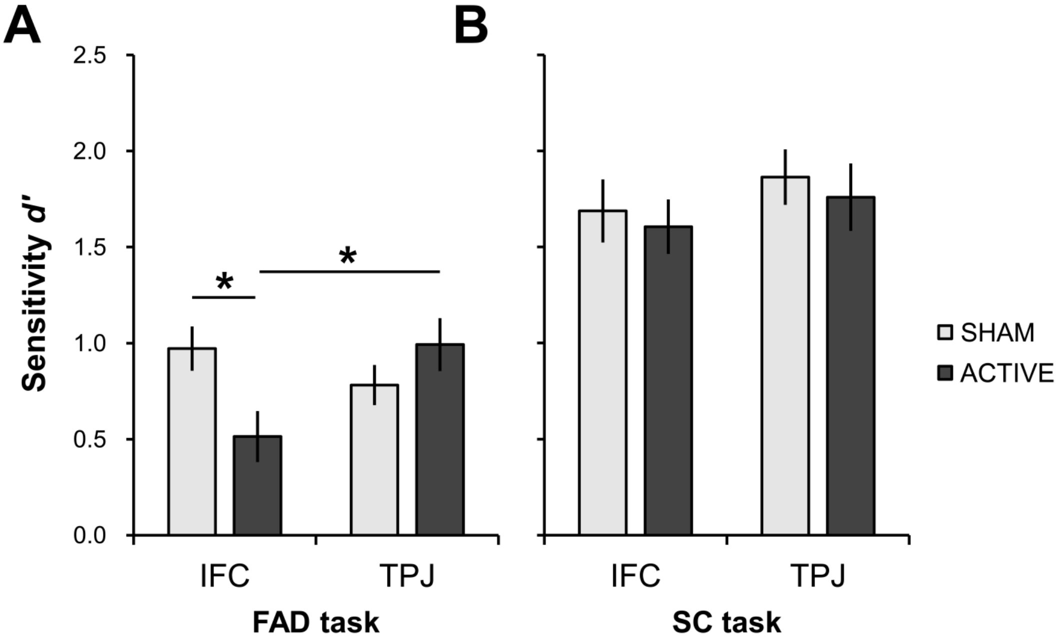
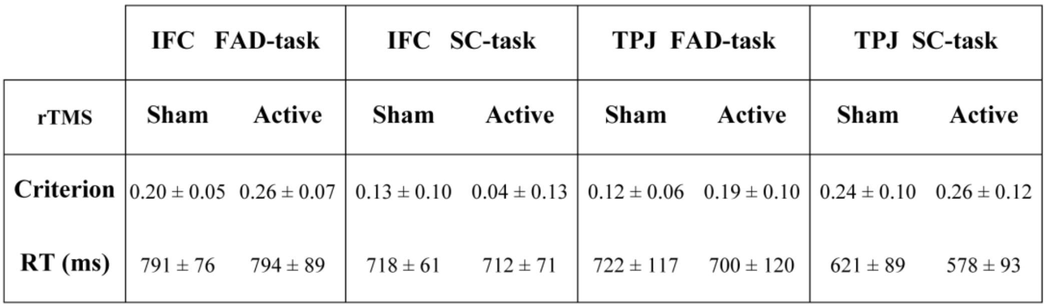


Figure 4. Mean sensitivity (d') in the FAD-task (A) and SC-task (B) of experiment 2. Light and dark grey columns represent Sham- and Active-rTMS respectively. IFC Active-rTMS brought about a reduction in sensitivity relative to Sham-rTMS in the FAD-task (A). No change in sensitivity due to rTMS was observed in the SC-task (B). Asterisks indicate significant comparisons (p < 0.05). Error bars denote s.e.m.

The Task x rTMS x Stimulation site ANOVA performed on Criterion revealed no main effects or interactions (all F < 2.56, p > 0.12; Table 1). The Task x rTMS x Stimulation site ANOVA performed on RTs showed only a non-significant main effect of Task (F1,26 = 3.04, p = 0.09), with slightly faster responses in the SC-task (mean RT

± s.e.m.: 657 ms ± 175) compared to the FAD-task (751 ms ± 201). No other main effect or interactions (all F < 1.38, p > 0.25) approached statistical significance (Table 1).

Table 1 Response Time and Criterion (mean ± s.e.m.) data collected in experiment 2



	IFC FAD-task		IFC SC-task		TPJ FAD-task		TPJ SC-task	
rTMS	Sham	Active	Sham	Active	Sham	Active	Sham	Active
Criterion	0.20 ± 0.05	0.26 ± 0.07	0.13 ± 0.10	0.04 ± 0.13	0.12 ± 0.06	0.19 ± 0.10	0.24 ± 0.10	0.26 ± 0.12
RT (ms)	791 ± 76	794 ± 89	718 ± 61	712 ± 71	722 ± 117	700 ± 120	621 ± 89	578 ± 93

In sum, interference with left IFC, but not with left TPJ, impaired performance in the FAD-task, suggesting that action simulation processes in IFC may be fundamental for visual discrimination of FAs and TAs. Since these two visual conditions shared the same apparent goal (lifting/placing), but differed in terms of spatio-temporal (e.g. variability of movement duration, mean acceleration peak) and configurational (e.g. max wrist angle) features, the suggestion is made that IFC is critically involved in the processing of kinematic cues that are necessary for inferring deceit from observed actions. No detrimental effects of IFC-rTMS were found in the SC-task requiring simple processing of the spatial features of seen actions. However, the SC-task was easier than the FAD-task. To rule out that the differential effect of IFC-rTMS in the two tasks was simply due to a ceiling effect, we performed a third rTMS experiments in which FAD- and SC-tasks were matched for difficulty.

4.5 Experiment 3

The rTMS x Task ANOVA performed on d’ revealed a significant interaction (F1,14 = 5.49, p = 0.03; Figure 5) accounted for by lower performance in the FAD-task during active-rTMS (0.93 ± 0.24) compared to sham-rTMS (1.39 ± 0.36; p = 0.006) and compared to SC-task performance during active-rTMS (1.42 ± 0.36; p = 0.01) and sham-rTMS conditions (1.40 ± 0.36; p = 0.02). By contrast, no change in performance due to rTMS was found in the SC-task (p = 0.89) and no main effects of rTMS or Task were found (all F < 2.11, p > 0.17).

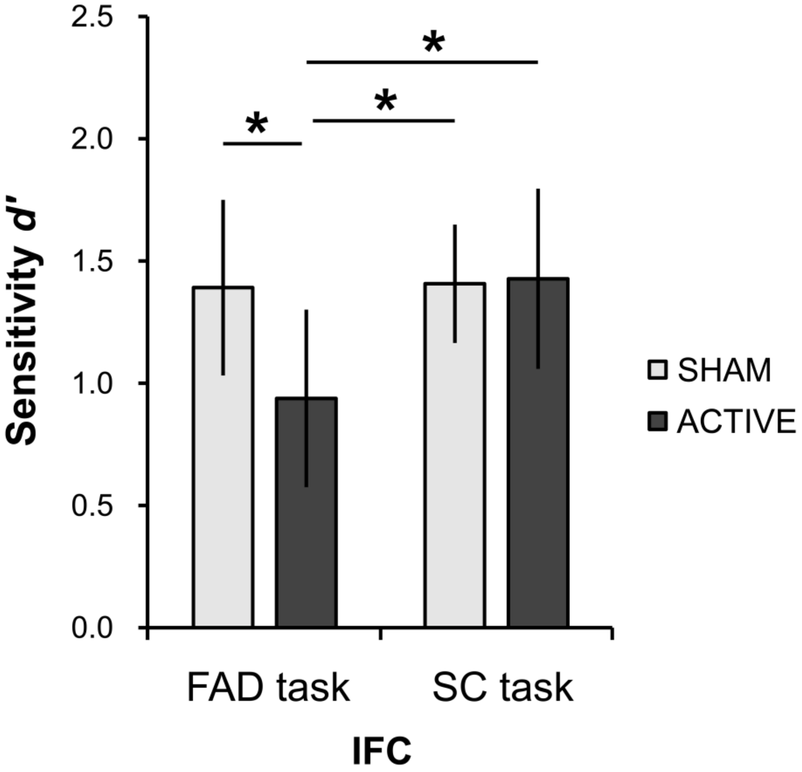


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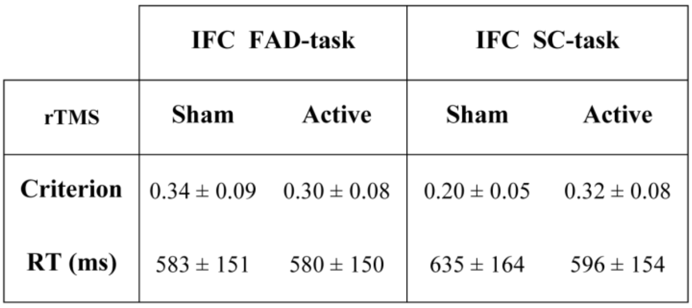
Figure 5. Mean sensitivity (d') in the FAD-task (A) and the SC-task (B) of experiment 3. Light and dark grey columns represent sham- and active-rTMS respectively. Active-rTMS over IFC reduced sensitivity in the FAD- but not in the SC-task. Asterisks indicate significant comparisons ($p < 0.05$). Error bars denote s.e.m.

Table 2 Response Time and Criterion (mean ± s.e.m.) data collected in experiment 3



	IFC FAD-task		**IFC SC-task**	
rTMS	**Sham**	**Active**	**Sham**	**Active**
Criterion	0.34 ± 0.09	0.30 ± 0.08	0.20 ± 0.05	0.32 ± 0.08
RT (ms)	583 ± 151	580 ± 150	635 ± 164	596 ± 154

The rTMS x Task ANOVAs performed on Criterion (all $F < 2.70$, $p > 0.122$) and RTs (all $F < 1.00$, $p > 0.33$) showed no main effects or interaction (Table 2).

4.6 Discussion

Perceiving FAs affects motor resonance

People can easily identify deceptive intents from observed behavior on the basis of stored internal models of the observed action (Runeson and Frykholm, 1983). It is held that FA recognition relies on the reading of kinematic cues that violate observers' predictions of the ongoing observed action (Bond et al., 1992; Frank and Ekman, 1997). Acquisition of internal action models through motor experience strengthens simulative activity in the motor system (Calvo-Merino et al., 2006; Cross et al., 2006; Fourkas et al., 2008) and improves the ability to read others' action kinematics (Casile and Giese, 2006; Aglioti et al., 2008). Notably, athletes present a superior ability to recognize FAs in their sport domain (Jackson et al., 2006; Sebanz and Shiffrar, 2009). Taken together, these studies suggest a link between action simulation and the ability to infer deceptive intents from observed kinematics. Results from experiment 1 provide the first neural evidence for this link by showing specific modulation of motor resonance during FA recognition. During execution, we found that the target FDI muscle critically contributed to the motor control of lifting and placing and was modulated as a function of the real weight of the cube, suggesting that internal models of lifting/placing may encode grip force and thus FDI involvement. During action observation, FDI MEPs were larger for apparently heavy than for apparently light cubes. This suggests that the motor cortex was modulated by the apparent grip force that could be predicted on the basis of a coarse categorization of the observed movement as quick/slow (suggesting light/heavy weights, respectively; Alaerts et al., 2010b). Notably however, MEPs were also larger for FAs relative to TAs, indicating that processing of subtle kinematic cues violating the predicted actions (and revealing the deceptive intent) was associated with an additional facilitation of the FDI representation. Greater facilitation was not simply due to a semantic coding of, or arousal responses to, FAs, as evidenced by the different modulation detected in the FCR control muscle (see Result section).

In keeping with predictive theories of action perception (Wilson and Knoblich, 2005; Kilner, 2011) we suggest that during FAD, the motor system generates an initial prediction about the action and its expected kinematics. This prior prediction is then compared with the incoming sensory input. When a violation of the predicted action is detected (FAs), a prediction error signal reaches those motor representations (e.g. FDI) whose predicted activity did not match the actual seen kinematics. Processing these violations may be functionally akin to the detection of an error in the action plan. In keeping with this idea, studies indicate that watching erroneous actions increases premotor and motor cortex activity (Manthey et al., 2003; van Schie et al., 2004; Koelewijn et al., 2008). Moreover, basketball players watching erroneous basket throws show increase of motor facilitation relative to correct throws (Aglioti et al., 2008). Our study expands this body of evidence by suggesting that during FAD, both prior predictions and their violations are encoded in the corticospinal system with a high degree of topographic specificity. Experiments 2 and 3 highlight the IFC as the possible neural locus where these processes occur and establish its critical role in visual recognition of FAs.

Virtual lesion to IFC impairs deceptive actions recognition

In experiment 2, we selected two key regions within the AON and Mentalizing networks (left IFC and left TPJ), and applied online-rTMS to test their causative role in FAD. We found that IFC-rTMS but not TPJ-rTMS reduced perceptual sensitivity in the FAD-task. No change was found in the SC-task, suggesting that reduction in performance in the FAD-task was not due to unspecific effect of IFC-rTMS. However, the SC-task was easier than the FAD-task. We thus matched task difficulty and performed a third experiment in which rTMS was again applied to IFC. Results from experiment 3 replicated the selective FAD-task impairment. These findings provide the first evidence that IFC is critical for inferring deceit from observed kinematics. Previous research has suggested that activity in IFC is sensitive to action goals (Thioux et al., 2008; Gazzola et al., 2007) and intentions (Iacoboni et al., 2005; Liepelt et al., 2008), but also to action kinematics (Majdandzic et al., 2009; Hesse et al., 2009), suggesting that IFC may contain multiple action representations. Importantly, recent investigations have started to show that IFC is necessary for action understanding (Avenanti and Urgesi, 2011; Moro et al., 2008; Pazzaglia et al., 2008). In a relevant study, Pobric and Hamilton (2006) demonstrated that IFC is required to estimate the weight of objects from the observation of lifting actions. In that study, IFC-rTMS but not occipital-rTMS reduced accuracy in the weight-judgment task, but not in a pure ‘temporal’ control-task requiring participants to estimate how long the hand was visible in the movies. These findings suggested that IFC was necessary for visual processing of action kinematics rather than for a simple evaluation of temporal information. However, RTs were not collected and the control tasks were clearly easier than the main task. Therefore, speed-accuracy trade-off or ceiling effects could not be excluded. Our study provides causative evidence that the IFC is not only sensitive to action kinematics and intentionality but is also critical for inferring deceit from observed kinematics. By using Signal detection theory analysis we demonstrated that IFC-rTMS (but not TPJ-rTMS) reduces perceptual sensitivity but not response bias, demonstrating a clear reduction in the ability to discriminate FAs and TAs. Moreover, IFC-rTMS did not impair performance in the SC-task which required maintenance of a visuo-spatial representation of the hand path without the necessity to process spatiotemporal (e.g. acceleration) or configurational (e.g. wrist angle) cues that were critical for FAD. Importantly, the detrimental effect of IFC-rTMS in the FAD- but not in the SC-task was not due to a ceiling effect. Moreover, the analysis of RTs rules out that detrimental effects of rTMS were due to a speed-accuracy trade-off. These findings highlight the specific contribution of the anterior note of the AON to action perception. Left IFC appears critical for visual discrimination of actions that differ in complex configurational and spatio-temporal features rather than in simple visuo-spatial (e.g. trajectory) or temporal (as suggested by Pobric and Hamilton, 2006) features of seen actions. In sum, experiments 1-3 suggest that the analysis of action dynamics carried out in the motor system is critical to detecting deceit in the actions of others.

Simulation vs mentalizing in FA recognition

It has been suggested that judging deceptive actions involves two phases, namely recognition of cues in behavior that violate the observer’s predictions; and ii) drawing inferences about intention on this basis (Bond et al., 1992; Frank and Ekman, 1997). The possible involvement of mentalizing in the recognition of deceits is consistent with the activation of the left TPJ when processing intentions during lying judgments (Harada et al., 2009). This region is active when reflecting on others’ beliefs and intentions (Saxe and Powell, 2006; Young et al., 2011) and its lesioning impairs the understanding of these mental states in others (Samson et al., 2004; Chiavarino et al., 2010). Nonetheless, our data suggest that TPJ is less involved than IFC in FA recognition. This may suggest that (at least in the left hemisphere) inferential and mentalizing processes may be epiphenomenal to the detection of deceits from observed body movements which critically relies on action simulation implemented in the human AON.

5 General Discussion

The presented studies showed the modulation (Study1 and 3) and functional role of sensorimotor areas (Study2 and 3) during passive (Study1) and behavioural tasks (Study2 and 3) requiring actions observation. Subjects were asked to perform low and high level information processing from visual inspection of static and dynamic hands' posture subtending different sensory features (Study2) or different actor's intentions (Study3).

In Study1 we explored the possible functional involvement of the human motor system in the anticipatory representation of observed actions by recording the cortico-spinal facilitation during observation of snapshots depicting specific finger configuration (e.g., large or small finger aperture) and snapshots depicting specific temporal phases (e.g., start or end of hand actions). In particular, we tested whether mirror motor facilitation during implied action stimuli observation was higher when extrapolating dynamic information about upcoming than past action phases. We found that observing the start and middle postures of grasp and flick actions engendered a significantly higher motor facilitation than observing their final postures. In contrast, observing the final postures of both grasp and flick actions did not activate the motor system. Importantly, the finger configuration in the start posture of grasp actions was comparable with the end posture of flick actions, whereas finger configuration of the end posture of grasp actions was comparable with that in the start position of flick actions.

Furthermore, the EMG recording during action execution showed that muscular activation increased over time during both grasp and flick actions, reaching its maximum during the middle and end phases of the movements. Thus, differential mirror motor facilitation during start and end postures cannot be ascribed to 1) mere reading out of finger aperture and muscular activation at different postures; nor to 2) any differential ability in recognizing the actions represented in the static snapshots because action discrimination performance was comparable for the 3 action phases. The modulation of motor facilitation was independent of the perceived intensity of hand or object implied motion in start, middle, and end postures. Indeed, although ratings of implied hand action were maximal for start and middle grasp postures, no difference was observed between the 3 phases of flick actions. On the other hand, ratings of the implied object motion were maximal for flick end postures, which exerted minimal facilitation on corticospinal excitability.

Thus, a main point of novelty of Study1 is that the results provide compelling evidence that the frontal component of the observation-execution matching system is preferentially activated by the anticipatory simulation of future action phases and thus plays an important role in the predictive coding of others' motor behaviors.

In Study2 we showed that active-cTBS delivered over SI (Study2) just before the participants were asked to evaluate the weight of a box lifted by an actor altered the performance compared to the sham condition. This did not happen in the control bouncing ball task whose cTBS and sham condition were comparable. These findings indicate that SI plays a causal role in extracting somatosensory features (heavy/light) from observed action kinematics and expand current view on action observation suggesting a fundamental role of primary sensory cortices in others action understanding.

Finally, we demonstrated the role of premotor areas and the modulation motor areas during the observation and recognition of deceptive actions (Study3). Action simulation and non-motor inferential (i.e., mentalistic) processes have often been conceptualized as mutually exclusive. However, recent theoretical (Uddin et al., 2007; Keysers and Gazzola, 2007) and empirical (Brass et al., 2007; de Lange et al., 2008; Schippers et al., 2009; Spunt et al., 2011) work suggests that simulation and mentalizing may have complementary roles in social cognition. Therefore, a central aim of cognitive neuroscience is to clarify the circumstances in which these processes are critical for understanding others' behavior (Mitchell, 2008, 2009). In Study3, we provided correlational and causative evidence that action simulation is called into play when detecting deceptive intents in the body movements of others. In Study3-experiment 1, we used single-pulse TMS to test whether motor resonance is modulated during discrimination of FAs and TAs (FAD-task). We found that watching an actor lifting and placing objects facilitated the observers' motor system (Fadiga et al., 2005), with greater muscle-specific facilitations for apparently heavier weights (Alaerts et al., 2010a). Importantly, processing of FAs strongly facilitated the motor system in a muscle-specific manner, suggesting that action simulation is sensitive to deceptive movements. To test whether action simulation is also required for FA recognition, in Study3-experiment 2 we applied rTMS over the anterior node of the AON (the left IFC) during performance of the FAD-task and a control task. As a further control, we applied rTMS over a key node of the Mentalizing network, namely the left TPJ. We found that IFC-rTMS but not TPJ-rTMS impaired FAD-task (but not control task) performance, and in Study3-experiment 3, we replicated this selective detrimental effect. These findings strongly demonstrate that action simulation is critical for inferring deceits from observed kinematics.

In summary, these extensive studies provided exiting and novel results for the role of a sensorimotor network comprising sensory and premotor areas for others action understanding and intention reading. Firstly, these data clearly confirm the crucial role of the action observation-execution matching system initially described in monkeys by di Pellegrino and colleagues (di Pellegrino et al., 1992) for others action understanding, secondly these data remark its relevance for current theoretical models of action observation and clearly expand its role to social cognition.

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List of publications

2012

1) **Tidoni E**, Borgomaneri S, di Pellegrino G, Avenanti A (2012) Action simulation plays a critical role in deceptive action recognition. The Journal of Neuroscience, *InPress.*

2) Sacheli LM, Candidi M, Pavone EF, **Tidoni E**, Aglioti M (2012) And Yet They Act Together: Interpersonal Perception Modulates Visuo-Motor Interference and Mutual Adjustments during a Joint-Grasping Task. PlosOne, *InPress.*

3) Sacheli LM, Candidi M, Pavone EF, **Tidoni E**, Aglioti M (2012) Kinematics fingerprint of Lead and Follow in real hand-to-hand cooperative interactions. Experimental Brain Research, *Under Review.*

4) Valchev N, **Tidoni E**, Hamilton A, Gazzola V, Avenanti A (2012) Primary somatosensory cortex necessary for the perception of other people's action: a continuous theta-burst TMS experiment. The Journal of Neuroscience, *Under Review.*

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1) Urgesi C, Maieron M, Avenanti A, **Tidoni E**, Fabbro F, Aglioti SM (2010) Simulating the future of actions in the human corticospinal system. Cerebral cortex 20:2511–21.

Overview of Publication Status of Chapters in Thesis

You are kindly requested to indicate which of the thesis chapters are original, have been submitted for publication, or have been accepted/published by filling out the first column (chapter number and title) and tick the appropriate box in the last four columns:

Chapter number and title	Original text (not published before)	Submitted: no feedback received	Submitted: revision requested or revision submitted	Accepted/published (specify journal or book)
1. Overview	x			
2. Study1: Simulating the Future of Actions in the Human Corticospinal System				Cerebral Cortex
3. Study2 : Primary somatosensory cortex necessary for the perception of other people's action: a continuous theta-burst TMS experiment.			The Journal of Neuroscience	
4. Study3 : Action simulation plays a critical role in deceptive action recognition				The Journal of Neuroscience
5. General Discussion	x			