



UNIVERSITY OF ROME “LA SAPIENZA”

Faculty of Psychology 1, Department of Psychology.

**European PhD course in “Cognitive plasticity and
rehabilitation”**

XXI cycle

**“Bodily form, actions and motor skills’ neural representations:
Transcranial Magnetic Stimulation studies.”**

Coordinator: Prof. Salvatore Maria Aglioti _____

Supervisor: Prof. Salvatore Maria Aglioti _____

PhD student: Dott. Matteo Candidi

TABLE OF CONTENTS

1. Introduction.	3
2. Implied action observation.	4
3. Mapping implied body actions in the motor cortex (Study 1).....	7
3.1 Methods.	7
Participants.	7
Electromyography recording and transcranial magnetic stimulation.	7
Stimuli and procedure.	9
Data Handling.	12
3.2 Results.	12
Experiment 1.....	12
Experiment 2.....	14
Experiment 3.....	17
3.3 Discussion.....	20
4. Neural substrates of action and body form representation.	24
5. Premotor cortices role in action anticipation.....	24
6. Ventral and dorsal visual stream.....	26
7. Representation of body identity and action in Extrastriate Body Area and ventral Premotor cortex (Study 2).....	29
7.1 Methods.	29
Participants.	29
Stimuli and Tasks.....	30
Transcranial Magnetic Stimulation.....	32
Procedure.....	34
Data Handling.....	35
7.2 Results.	37
7.3 Discussion.....	38
8. Neural representations of abstract motor knowledge.....	40
9. Grounding the skills of a motorically expert model in the cortico-spinal system of a (naïve) onlooker (Study 3).	45
9.1 Methods.	46
Experiment 1.....	46
Participants.	46
Electromyographic (EMG) and TMS recording.....	46
Visual stimuli.....	48
Procedure.....	48
Data handling.....	50
9.2 Results Experiment 1.	50
9.3 Experiment 2.....	52
9.4 Results Experiment 2.	53
9.5 Discussion.....	55
10. General discussion.	61
11. References.	65
12. Acknowledgements.....	75
13. APPENDIX: ORIGINAL PUBLICATIONS.....	76

1. Introduction.

Recent years have seen the development of new neurophysiological techniques that deepened the knowledge of neural processes underlying simple as well as complex brain mechanisms of behaviour and cognitive processes. Knowledge about body and motor representations in the brain has advanced much through the discovery of mirror neurons in monkeys and their putative homologous counterpart in humans. Simulative-like mechanisms have been proposed to be at the base of perceptive and cognitive functions. The present work focuses on neural underpinnings of visual body and action perception and motor skills representation in the motor system.

These issues are at the core of plastic neural changes in action learning, understanding and higher cognitive functions as abstract motor reasoning and identity categorization.

This thesis reports three studies in which these domains have been studied through single-pulse TMS and high-frequency event-related repetitive TMS procedures.

2. Implied action observation.

Satisfactory and functional interactions with a dynamic world are only provided by anticipatory perceptual mechanisms (von Holst, & Mittelstaedt, 1950). To interact with objects moving under physical laws and others' body performing actions, indeed, humans need to continuously predict the objects' trajectories and humans' actions. The extreme case of movements' trajectory prediction is evident when nothing more than a static image of a given dynamic event is available to watchers. During observation of static images of moving objects, the brain is able to extract dynamic information about the trajectory of the object. This phenomenon, known with the name of *representational momentum* (Freyd, 1983), is behaviourally evident as people tend to erroneously recognize a previously seen image implying motion with a snapshot depicting the same event in a future moment. Neuroimaging studies have reported that medio-temporal areas (MT/MST), which process actual movement perception (dot shifting, radial gratings, oscillating low-contrast rings), are also activated by the perception of images that simply imply motion (Zeki et al., 1991; Dupont et al., 1994; Tootell et al., 1995). The ability of the brain to anticipate dynamic information from static images has been studied also for images of human actions (Verfaillie and Daems, 2002). Observation of static images of biological entities that merely imply an action, activates MT (Kourzy & Kanwischer, 2001; Senior et al., 2000). Monkeys' posterior Superior Temporal Sulcus (STS), situated just above MT and greatly connected to it (Ungerleider, & Desimone, 1986), responds to the presentation of the final posture of trunk movements (Jellema & Perrett, 2003). Coherently with this evidence, static body images activates in humans a temporo-occipital complex suggesting dynamic motor extraction from static image (Peigneux et al., 2000). Biological movement perception is able to activate the posterior part of the superior temporal sulcus (Grossman

et al., 2000). Different studies have reported activation of STS for eye, hand and whole body movements (review in Puce & Perret 2002).

Beside temporo-occipital brain regions, specifically devoted to the analysis of complex motion (MT/MST, STS), the perception of biological motion portrayed through a specific kind of stimulus termed “point-light-display”, that conveys no form information of the moving object, is capable of modulating neural activity also in premotor cortices (Saygin et al., 2004). In the last 20 years, evidence from studies on monkeys and humans have demonstrated that action observation activates premotor regions (Rizzolatti & Craighero 2004). This evidence have offered insights into the motor system’s role in action representation (for a review see Rizzolatti & Craighero, 2004). Far from being “merely” the brain area where actions are programmed (premotor cortices) and motor commands are sent to M1, the motor system has shown to be sensitive to action observation. Single cell recordings have demonstrated that cells in monkeys’ F5 area (inferior frontal gyrus) fire both during active grasping execution and passive grasping observation (i.e. mirror neurons, di Pellegrino et al., 1992). Similar neurons have then been described in monkeys inferior parietal lobule (IPL) (Fogassi et al., 2005). Monkeys’ premotor activity for action observation is insensitive to many low-level properties of the stimulus as the perspective and the identity of the individual being observed.

Evidence for the existence of a similar neurophysiological mechanism in humans has grown in the last years. Interactions between action execution and observation are widely reported at a behavioural level (Prinz, 1997). Behavioural, neurophysiological, and neuropsychological studies suggest that action execution and observation are represented in commensurable formats and share the same neural underpinnings (Brass, et al., 2000; Craighero et al., 2002; Wohlschlagel & Bekkering, 2002; Prinz, 2002; Prinz 1997; Buccino et al., 2001; Grezes, & Decety, 2001; Saygin et al., 2004). Importantly, mere action observation influences motor representations and plays an important role in learning new

movements (Stefan et al., 2005; Celnik et al., 2006). Imaging studies have described somatotopic activations of premotor and parietal cortices for action observation (Buccino et al., 2001). TMS studies have shown that the excitability of the corticospinal system is enhanced during action observation and follows somatotopic rules, as only the muscle that would be involved in the execution of the observed action is facilitated (Fadiga et al., 1996). This effect is thought to reflect cortical facilitation rather than peripheral, as Baldissera and co-workers demonstrated by measuring the H-reflex of hand muscles of passive watchers during action observation (Baldissera et al., 2001). The size of the monosynaptic reflex, indeed, followed a reverse pattern with respect to that of motor cortex excitability as revealed with TMS showing that overt imitation of the observed action may be prevented by peripheral phasic inhibition.

Although movement information can be extracted or inferred from static images, so far there have been no investigations of the possible mapping of snapshots implying biological or non biological movements in the motor system. In three experiments, we used single-pulse TMS to determine whether the observation of snapshots of hand postures stimuli, which may or may not imply motion, can engender a selective mirror facilitation of cortico-spinal motor representations.

3. Mapping implied body actions in the motor cortex (Study 1).

3.1 Methods.

Participants.

Sixteen healthy individuals (eight women) aged 20–29 (mean, 23 years) participated in experiment 1; sixteen healthy individuals (six women) aged 20–29 (mean, 23.8 years) participated in experiment 2; sixteen healthy individuals (ten women) aged 19–33 (mean, 23.3 years) participated in experiment 3. None of the participants took part in more than one experiment. All participants were right-handed according to a standard handedness inventory (Briggs & Nebes, 1975), were native Italian speakers with normal or corrected-to-normal visual acuity in both eyes and were naïve as to the purposes of the experiment. Information about the experimental hypothesis was provided only after the experimental tests were completed. Participants gave their written informed consent and were paid 15 € for their participation in the study. The procedures were approved by the local ethics committee and were in accordance with the ethical standards of the 1964 Declaration of Helsinki. None of the participants had neurological, psychiatric, or other medical problems or any contraindication to TMS (Wasserman, 1998). No discomfort or adverse effects during TMS were reported or noticed.

Electromyography recording and transcranial magnetic stimulation.

Motor evoked potentials (MEPs) were recorded simultaneously from the FDI and abductor digiti minimi (ADM) muscles (experiments 1 and 2) and from the FDI and the extensor carpi radialis (ECR) muscle (experiment 3) of the right hand. It is worth noting here that the FDI muscle is strongly involved in the execution of pincer grips; by contrast, the ADM

muscle does not play a major role in the execution of pincer grips but is involved in the execution of gross grasping movements. The ECR muscle does not have any specific role in the execution of either gross or precision grasping movements. Electromyographic (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 - 3 kHz) and digitized by means of a Viking IV electromyography equipment (Nicolet Biomedical, Madison, WI). The sampling rate of the EMG signal was 20 kHz. A pre-stimulus recording of 20 ms was used to check for the presence of EMG activity before the TMS pulse. To further control for the presence of unwanted background EMG activity before the magnetic pulse, the signal from both muscles was additionally displayed in separate channels set at high sensitivity (50 μ V). 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-eight stimulation coil (Magstim polyurethane-coated coil), connected to a Magstim 200 Rapid (The Magstim Company, Carmarthenshire, Wales), producing a maximum output of 2 T at the coil surface (pulse duration, 250 μ s; rise time, 60 μ s). The coil was 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. We chose it 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 with constant intensity. Participants wore a tightly fitting

bathing cap on which the scalp positions for stimulation were marked. The coil was held by hand, and its position with respect to the marks was checked continuously. The rMT, defined as the lowest stimulus intensity able to evoke five out of ten MEPs with an amplitude of at least 50 μ V, was determined by holding the stimulation coil over the OSP. Since MEPs were simultaneously recorded from two muscles in all experiments, OSP and rMT were determined by using the higher threshold muscle, namely, the ADM, in experiments 1 and 2, and the ECR in experiment 3. With this procedure a clear and stable signal was obtained from both targeted muscles in all participants in all experiments. Indeed, the distance between the OSPs for the targeted muscles was within the spatial resolution of the employed coil (approximately 1 cm; Krings et al., 1998). During the recording session, stimulation intensity was 130% of the rMT and ranged from 50% to 92% (mean = 67.1%) of the maximum stimulator output in experiment 1, from 55% to 93% (mean = 68.4%) in experiment 2 and from 57% to 79% (mean = 69.9%) in experiment 3. MEPs peak-to-peak amplitude (in mV) was collected and stored on a computer for off-line analysis.

Stimuli and procedure.

Stimuli were colour pictures taken with a digital camera and modified by means of the Adobe Photoshop software (Adobe Systems Incorporated, San Jose, CA). Body stimuli represented the right hand of a man (26 years) and a woman (29 years) during a pincer grip movement. Presenting two different hand stimuli allowed minimizing habituation and loss of attention (Fig. 1). The hands of the two models were presented in an equal number of trials. In experiment 1 three types of snapshots depicting different hand motion phases were presented: a still hand laying on a table (still hand), a hand in the middle of the grasping movement (implied motion hand), and the end posture of the grasping movement

(end posture). To rule out that the mere observation of graspable objects may *per se* activate the motor system (Chao and Martin, 2000; Nelissen et al., 2005), none of the action snapshots contained any objects. Hand stimuli were presented on a uniform background and subtended an $18.53^\circ \times 19.31^\circ$ region. In experiments 2 and 3 the same still- and moving-hand stimuli of experiment 1 were used. In experiment 2 we assessed the specificity of the implied motion effect found in experiment 1 by presenting pictures of two different exemplars of airplanes. Presenting two different airplane stimuli allowed minimizing habituation and loss of attention (Fig. 2). Each airplane was depicted while still on the ground (still object) or during take off (implied motion object). A background context was included in the images to enhance the difference in the implied motion effect induced by still airplanes and airplanes taking off. Pictures of airplanes subtended an $18.53^\circ \times 11.26^\circ$ region. In experiment 3 we tested the selectivity of the implied motion effect by using a different type of object stimuli, namely, pictures of two different flowing waterfalls (implied motion objects). As static control we presented pictures of the same frozen waterfall (still object). Presenting two different waterfall stimuli allowed minimizing habituation and loss of attention (Fig. 3). One type of waterfall picture subtended an $18.53^\circ \times 19.31^\circ$ region, the other an $18.53^\circ \times 6.98^\circ$ region. In experiments 2 and 3 the presented images corresponded to the factorial combination of stimulus type (body, object) and motion (still, implied motion). For each body or non-body category, corresponding still and motion stimuli were roughly matched for colour, luminance and viewing perspective. Stimulus-presentation timing, EMG-recording and TMS triggering, as well as randomization of stimuli in a block, were controlled using E-prime V1.1 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 from 267 to 33 ms before the offset of the stimulus to avoid any priming effects that could affect MEP size. An 8.8 s blank screen was presented before the next trial. Therefore, the inter-

pulse interval ranged from 10.03 to 10.3 s. The choice of the inter-pulse interval was based on research by Chen et al. (1997) that showed no change in cortico-spinal excitability with repetitive TMS at 0.1 Hz for 1 hr (Chen et al., 1997). Participants were tested in one experimental session lasting approximately 90 minutes. They sat in a comfortable armchair in a dimly lit room 80 cm away from a 19 in monitor (resolution, 800 x 600 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. They were also instructed to pay attention to the stimuli presented on the screen and were informed that at the end of the session questions would be asked about the observed body (gender of the models, orientation of the hand, type of represented action) and non body (color and type of airplane and waterfall pictures) stimuli. No overt response was required at any time during stimuli presentation and data collection. The different observation conditions were presented in separate blocks counterbalanced according to a Latin square design. In experiment 1 three blocks (still hand, implied motion hand, end posture) were presented for a total of 48 trials; experiments 2 and 3 consisted of four blocks (still and implied motion hand; still and implied motion object) for a total of 64 trials. Each block consisted of 16 trials. A short rest was permitted before proceeding to a different block. Presentation of male and female hands (experiments 1-3) or of the two exemplars of objects (experiments 2 and 3) was randomized. In all experiments we recorded two series of 8 MEPs while participants kept their eyes closed. One series was recorded at the beginning and the other at the end of the experimental session. Comparisons of MEP amplitudes in these two series allowed us to check for any cortico-spinal excitability change related to TMS *per se*. After the TMS session, printed versions of the experimental stimuli were presented on separate A4 pages in a counterbalanced order. For each image participants were asked to judge the perceived intensity of the implied motion by marking

a vertical, 10 cm visual analogue scale (VAS) with 0 cm indicating “no effect” and 10 cm “maximal effect imaginable”.

Data Handling.

The absence of background EMG activity was confirmed by visual inspection of the data. In each experiment individual mean peak-to-peak MEPs amplitudes were separately calculated for each block (16 trials per cell) and each muscle. Trials with background activity preceding the TMS pulse or with a MEP amplitude higher or lower than 2 *SD* of the mean were discarded (4.3% in experiment 1, 4.4% in experiment 2, and 3.9% of the total in experiment 3). In experiment 1 mean raw MEPs amplitudes for each muscle and for VAS ratings were analyzed by means of series of one-way repeated-measures ANOVAs with hand motion phase (still, implied motion, end posture) as within-subjects variable. In experiments 2 and 3 MEPs and VAS data were analyzed by series of two-way repeated-measures ANOVAs with stimulus type (body, object) and motion (still, implied motion) as within-subjects variables. MEPs amplitudes recorded from each of the targeted muscles were entered in separate ANOVAs. Post-hoc multiple comparisons were carried out using the Newman-Keuls test. Series of paired-sample *t* tests (two-tailed) were used to compare amplitude of MEPs recorded from FDI, ADM, and ECR muscles in the eyes-closed conditions run at the beginning and at the end of the three experiments.

3.2 Results.

Experiment 1.

This experiment was aimed at testing whether merely observing snapshots of body images implying motion can act on the observer’s motor system. We compared cortico-spinal excitability during observation of static pictures showing still hands with observation of

static images of a hand caught in different phases of the same pincer grip movement. While in the intermediate phase the hand configuration was appropriate for grasping an object, in the end-posture phase the thumb and index fingers were in contact, thus making object grasping impossible. Figure 1 shows raw MEP amplitudes recorded from FDI and ADM muscles in the three observational conditions. Analysis of MEP amplitudes recorded from FDI during the different observation blocks yielded a significant effect of hand motion phase [$F(2,30) = 4.13$, $p = 0.026$]. Post hoc test showed that MEP amplitude was higher during observation of the implied motion phase ($2.27 \text{ mV} \pm 0.13 \text{ mV}$) than of the still ($1.97 \text{ mV} \pm 0.15 \text{ mV}$, $p = 0.043$) and end posture phases ($1.98 \text{ mV} \pm 0.14 \text{ mV}$; $p = 0.021$), which in turn did not differ from one another ($p = 0.932$). No significant effect of hand motion phase [$F(2,30) = 1.66$, $p = 0.207$] was found for MEPs recorded from ADM, that is not involved in the actual execution of pincer grip movements. Mean raw MEPs amplitudes during the two blocks with closed eyes run at the beginning and at the end of the experiment were not significantly different for either the FDI [$2.02 \text{ mV} \pm 0.21 \text{ mV}$ vs. $1.93 \text{ mV} \pm 0.17 \text{ mV}$; $t(15) = 0.48$, $p = 0.639$] or the ADM muscle [$1.45 \text{ mV} \pm 0.27 \text{ mV}$ vs. $1.53 \text{ mV} \pm 0.29 \text{ mV}$; $t(15) = -0.59$, $p = 0.564$]. This indicates that TMS *per se* did not induce any changes in cortico-spinal excitability in our experimental conditions. Analysis of VAS ratings of the motion implied by each stimulus showed a significant effect of hand motion phase [$F(2,30) = 41.59$, $p < 0.001$], because the subjective perception of implied motion was higher for the implied motion (6.21 ± 0.61) than for the still hand (0.47 ± 0.15 , $p < 0.001$) and end-posture snapshots (4.3 ± 0.6 , $p = 0.006$). Implied motion ratings for the end posture were significantly higher than for the still hand phase ($p < 0.001$). Thus, observation of the end posture phase yielded subjective reports of motion information in the absence of motor facilitation. Only observation of the intermediate phase was effective in modulating the excitability of the motor representation of the muscle involved in the execution of the very same movements.

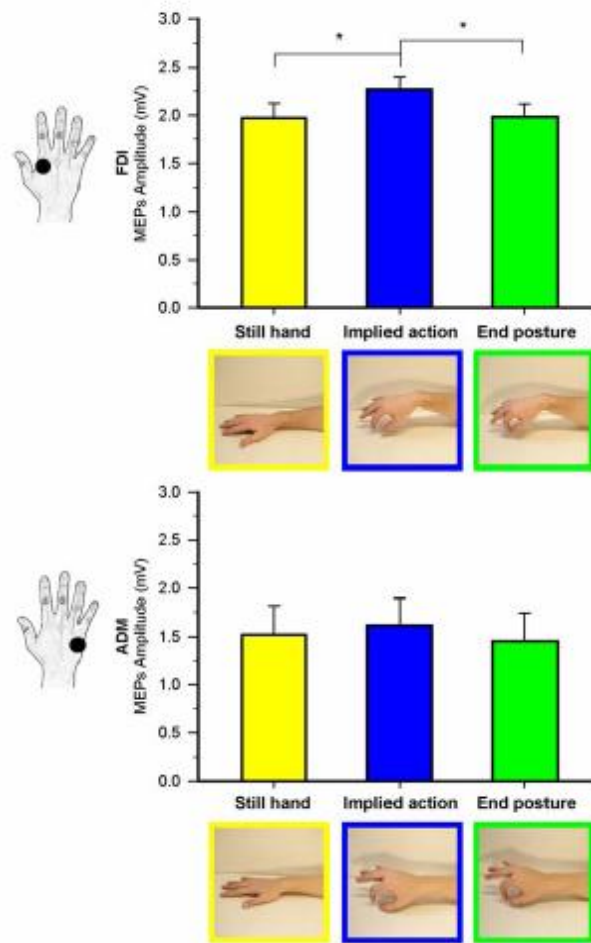


Figure 1. *Effect of observation of different implied motion phases of hand action in experiment 1. Raw mean amplitudes (in mV) of motor evoked potentials (MEPs) recorded from the first dorsal interosseous (FDI) and abductor digiti minimi (ADM) muscle during the three observational conditions. The male and female hand stimuli are shown on the FDI and ADM graphs, respectively. Error bars indicate standard errors; asterisks indicate significant comparisons.*

Experiment 2.

This experiment was aimed at testing whether motor facilitation can also occur during observation of implied motion object images. We used snapshots of airplanes that implied or did not imply motion and compared their effects on motor excitability with those of the

same hand pictures as in experiment 1. Figure 2 shows raw MEP amplitudes recorded from FDI and ADM muscles in the four observational conditions of experiment 2.

The two-way repeated measures ANOVA performed on MEPs amplitudes recorded from FDI revealed a significant main effect of stimulus type [$F(1,15) = 16.74, p = 0.001$], with higher MEPs amplitudes during observation of non body objects ($2.45 \text{ mV} \pm 0.22 \text{ mV}$) than during observation of body stimuli ($2.01 \text{ mV} \pm 0.21 \text{ mV}$). The main effect of implied motion was marginally significant [$F(1,15) = 3.55, p = 0.079$] because mean MEPs amplitude tended to be higher during observation of implied motion stimuli ($2.29 \text{ mV} \pm 0.22 \text{ mV}$) than during observation of still stimuli ($2.17 \text{ mV} \pm 0.2 \text{ mV}$). Crucially, however, a significant stimulus type x motion interaction [$F(1,15) = 4.83, p = 0.044$] suggested that the effect of implied motion on cortico-spinal excitability was specific for body stimuli. This was confirmed by post-hoc tests showing that MEP amplitude was higher during observation of implied motion hand images ($2.15 \text{ mV} \pm 0.23 \text{ mV}$) than during observation of still hand images ($1.88 \text{ mV} \pm 0.2 \text{ mV}, p = 0.012$). By contrast, no significant difference was observed between implied motion ($2.46 \text{ mV} \pm 0.22 \text{ mV}$) and still object stimuli ($2.43 \text{ mV} \pm 0.24 \text{ mV}, p = 0.825$). MEPs amplitude during observation of pictures showing still and implied motion airplanes was significantly higher than during observation of both still hands ($p < 0.001$ for both comparisons) and implied motion hands ($p < 0.02$ for both comparisons). Therefore, the significant effect of the interaction is explained by the fact that motor facilitation was elicited only by the observation of implied body actions.

The two-way ANOVA carried out on MEPs amplitudes recorded from the ADM muscle showed that the main effects of stimulus type [$F(1,15) < 1$] and motion [$F(1,15) = 2.89, p = 0.109$] and the stimulus type x motion interaction were non significant [$F(1,15) = 2.13, p = 0.165$]. Possible inherent differences in excitability of the cortical representations of the FDI and ADM muscle cannot explain the present differential modulation because previous research carried out with appropriate experimental conditions has already shown that the

responsiveness of the ADM muscle to TMS increases without changes in FDI muscle responsiveness (Romani et al., 2005). Comparisons of mean raw MEPs amplitude during the eyes-closed conditions blocks run at the beginning and at the end of the experimental session resulted in non significant differences for both the FDI [$1.8 \text{ mV} \pm 0.22 \text{ mV}$ vs. $1.83 \text{ mV} \pm 0.18 \text{ mV}$; $t(15) = -0.19$, $p = 0.85$] and the ADM muscle [$1.02 \text{ mV} \pm 0.15 \text{ mV}$ vs. $1.13 \text{ mV} \pm 0.17 \text{ mV}$; $t(15) = -1.26$, $p = 0.226$]. This indicates that the MEP modulations contingent upon action observation found in this experiment are not due to TMS per se.

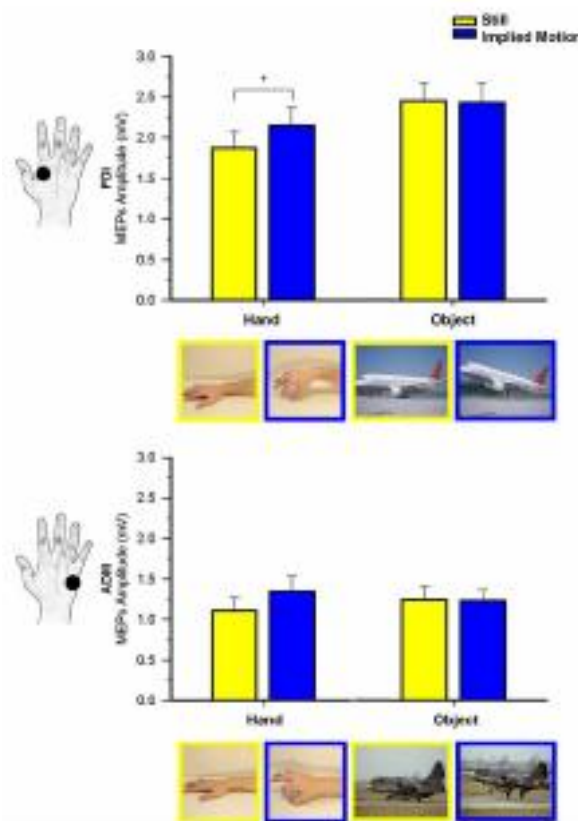


Figure 2. *Effect of observation of implied-hand and airplane motion in experiment 2. Raw mean amplitudes (in mV) of motor evoked potentials (MEPs) recorded from the first dorsal interosseous (FDI) and abductor digiti minimi (ADM) muscle during observation of still (yellow bars) and moving (blue bars) hand and object stimuli. The two types of still and moving hands and airplanes are shown on the FDI and ADM graphs respectively. Error bars indicate standard errors; asterisks indicate significant comparisons.*

The two-way repeated measures ANOVA carried out on VAS ratings showed the significance of the main effect of stimulus type [$F(1,15) = 10.4, p = 0.006$] because implied motion was higher for non body (4.93 ± 0.41) than for body stimuli (3.25 ± 0.29). The main effect of motion was highly significant [$F(1,15) = 64.05, p < 0.001$] with higher VAS ratings for implied motion stimuli (6.46 ± 0.41) than for still stimuli (1.72 ± 0.35). Importantly, the stimulus type x motion interaction was also significant [$F(1,15) = 6.15, p = 0.026$]. Post-hoc comparisons showed that mean VAS ratings for implied motion stimuli were significantly higher than for still stimuli in the case of both body (5.05 ± 0.44 vs. $1.45 \pm 0.45, p < 0.001$) and non body stimuli (7.87 ± 0.62 vs. $2.0 \pm 0.53, p < 0.001$). Mean VAS ratings were higher for implied motion airplane stimuli than for implied motion hands ($p < 0.001$). No significant difference was observed between still hands and still airplanes ($p = 0.408$). This pattern of results indicates the following: i) still hands and airplanes did not evoke perception of implied motion; ii) implied motion of airplanes was perceived as higher than that of hands. Therefore, the body selectivity of the motor facilitation did not reflect differences in the strength of implied motion perception.

Experiment 3.

Results of experiments 1 and 2 indicate that motor facilitation contingent upon perception of implied motion is selective for hand stimuli. However, in experiment 2 we found higher cortico-spinal excitability during observation of still and implied motion airplane pictures as compared to observation of still and implied motion hand pictures. It is known that observation of objects that can be manipulated or grasped activates motor and premotor areas (Beauchamp et al., 2002; Chao & Martin, 2000). Although real airplanes cannot be manipulated, the exemplars presented in our study might have been interpreted as toy models that can be mentally manipulated and grasped. To test this hypothesis we compared

motor facilitation contingent upon observation of implied body actions with that induced by observation of implied motion of water in waterfall images. Moreover, we further evaluated the muscular selectivity of motor facilitation during observation of implied hand actions by recording MEPs from the ECR, i.e., a forearm muscle not directly involved in the displayed grasping hand actions. Figure 3 shows raw MEP amplitudes recorded from FDI and ECR muscles in the four observational conditions of experiment 3. Analysis of MEPs amplitudes from FDI resulted in a non significant main effect of stimulus type [$F(1,15) < 1$] and motion [$F(1,15) = 1.43, p = 0.251$]. Crucially, the stimulus type x motion interaction was highly significant [$F(1,15) = 9.25, p = 0.008$]; a post-hoc test showed that mean MEP amplitude was higher during observation of implied motion hand images ($2.03 \text{ mV} \pm 0.37 \text{ mV}$) than during observation of still hand images ($1.64 \text{ mV} \pm 0.24 \text{ mV}, p = 0.027$). By contrast, no significant difference was observed between implied motion ($1.79 \text{ mV} \pm 0.25 \text{ mV}$) and still object stimuli ($1.93 \text{ mV} \pm 0.21 \text{ mV}, p = 0.825$). No other comparisons reached statistical significance (all $p_s > 0.07$), thus showing that the experimental effect was only due to higher cortico-spinal excitability during observation of body images with implied motion. Analysis of MEPs' amplitude recorded from the ECR muscle showed that neither the main effects of stimulus type [$F(1,15) = 1.82, p = 0.198$] and motion [$F(1,15) < 1$] nor the stimulus type x motion interaction [$F(1,15) < 1$] reached significance.

Comparisons of mean raw MEPs amplitude during the eyes-closed condition blocks run at the beginning and at the end of the experimental session resulted in non significant differences, for both the FDI [$1.66 \text{ mV} \pm 0.22 \text{ mV}$ vs. $1.46 \text{ mV} \pm 0.16 \text{ mV}; t(15) = 1.03, p = 0.32$] and the ECR muscle [$1.16 \text{ mV} \pm 0.12 \text{ mV}$ vs. $1.19 \text{ mV} \pm 0.12 \text{ mV}; t(15) = -0.47, p = 0.642$]. This indicates that, as in experiments 1 and 2, the MEP modulations contingent upon action observation found in this experiment are not due to TMS *per se*.

The two-way repeated measures ANOVA carried out on VAS ratings disclosed a significant stimulus type [$F(1,15) = 12.31, p = 0.003$] main effect in that higher implied motion ratings were assigned to non body (waterfalls: 4.6 ± 0.26) than to body stimuli (hands: 3.2 ± 0.41). The significance of the main effect of motion [$F(1,15) = 100.58, p < 0.001$] is due to the fact that implied motion stimuli (6.35 ± 0.33) were rated as more “dynamic” than still stimuli (1.45 ± 0.41).

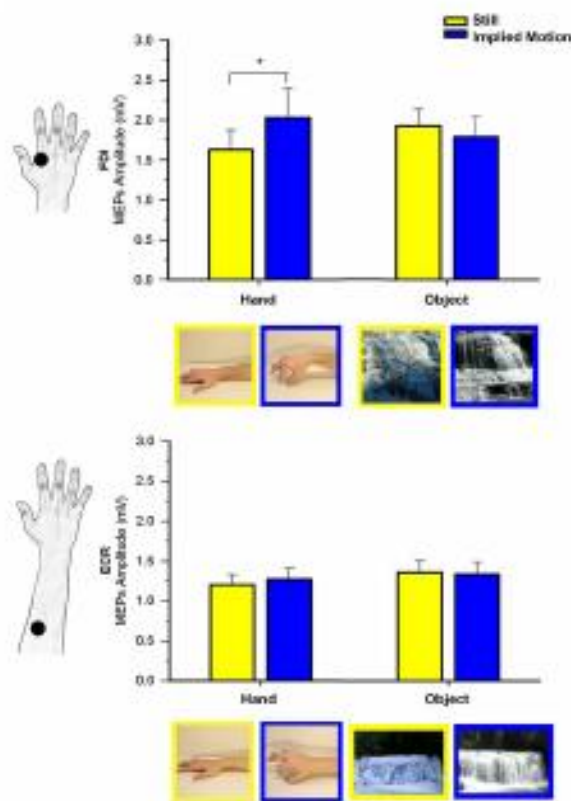


Figure 3. *Effect of observation of hands and waterfalls in experiment 3. Raw mean amplitudes (in mV) of motor evoked potentials (MEPs) recorded from the first dorsal interosseus (FDI) and extensor carpi radialis (ECR) muscle during observation of still (yellow bars) and moving (blue bars) hand and object stimuli. The two types of still and moving hand and waterfall stimuli are shown on the FDI and ECR graphs respectively. Error bars indicate standard errors; asterisks indicate significant comparisons.*

The stimulus type x motion interaction [$F(1,15) = 20.61, p < 0.001$] was also significant. Post-hoc comparisons showed the following: the mean VAS rating for implied motion stimuli was significantly higher than for still stimuli for both hands (4.98 ± 0.54 vs. $1.42 \pm 0.41, p < 0.001$) and waterfalls (7.72 ± 0.32 vs. $1.48 \pm 0.47, p < 0.001$). Interestingly, implied motion waterfalls were considered as more dynamic than implied motion hands ($p < 0.001$), while no significant difference was observed when comparing still waterfalls and still hands ($p = 0.883$). Thus, the pattern of implied motion perception for waterfall images was similar to that for airplane images (experiment 2). Crucially, however, no MEP modulation was found during the observation of non-graspable waterfalls either for still images or for implied motion images.

3.3 Discussion.

The present study shows for the first time that mirror motor mapping of actions occurs when dynamic information about body actions is inferred from static pictures of body postures. Moreover, the study suggests that perceiving implied motion from static snapshots is likely to trigger an anticipatory inner simulation of the temporal deployment of the observed body action. Our results indicate that even in the absence of explicit motion of the stimulus, observation of static photographs of pincer grips with implied motion produced a clear increase in cortico-spinal excitability with respect to observation of static images of still hands. Although entirely novel, this effect resembles that of observing actual actions reported in previous TMS studies of action observation (Fadiga et al., 2005). We found that the MEP modulation was selective, i.e., that it was present, only for the FDI muscle that would be activated during actual execution of the observed movement. By contrast, no motor facilitation was observed for ADM and ECR, which have no direct role in the execution of that action. The fact that cortico-spinal excitability

was higher during presentation of still and implied motion airplanes than during presentation of still and implied action (experiment 2) deserves discussion. On one hand, the comparable MEP amplitude during the viewing of still and implied motion airplanes may indicate the greater likelihood that these pictures will draw attention than hand pictures and, thus, induce general brain activation, including both premotor and motor areas. Ventral premotor cortex activity has been shown to increase during observation of complex non-manipulable objects (Kellenbach et al., 2003; Nelissen et al., 2005) and abstract visual scenes with dynamic properties (Schubotz & von Cramon, 2002). This explanation, however, does not account for the fact that during the observation of airplane images the MEP amplitude increase was apparent for the FDI muscle, which is active during actual fine grasping, but not for the ADM muscle, which is not. Another possible explanation is that the airplane images were interpreted by the observers as images of toys and, thus, mentally grasped at an implicit level. Indeed, toys are eminently manipulable, and it is known that the observation of toys, tools and other manipulable objects (Beauchamp et al., 2002; Chao & Martin, 2000), as well as of mimicked manipulation actions (Nelissen et al., 2005), activates premotor cortical areas. Results of experiment 3 also speak in favour of this hypothesis in that no MEP modulation was found during observation of non-graspable objects (waterfalls). Although implied motion was reported for flowing but not for frozen waterfalls, observation of these stimuli produced a comparable pattern of cortico-spinal excitability. Therefore, the motor facilitation evoked by perception of implied body actions is a specific process that cannot be explained by simple semantic coding of implied motion but seems to be linked to the activation of the frontal node of the mirror network that matches observed and performed actions. Static pictures of moving biological or non-biological objects typically convey dynamic information concerning the object's position just before and after the picture was taken. Therefore, processing implied motion is inherently temporal. Another important result of

the present study is that facilitation of the FDI muscle response was present during observation of the static image that was most suggestive of a hand caught in action, whereas it was absent not only during observation of a resting, relaxed hand but also during observation of a hand image suggesting a completed action. Although the implied motion of the latter image was subjectively rated as higher than that of the resting hand, this was apparently insufficient to engage the motor system. This dissociation between subjective reports and MEP modulation indicates that semantic representation of the movement cannot be the sole explanation of the motor facilitation contingent upon observation of implied actions. One likely account for the different motor modulation induced by the two types of implied motion hand stimuli is that the one caught in action conveyed dynamic information about forward and backward action paths, while the final posture hand provided information only about backward action paths. This would suggest that the motor system was maximally activated by the extrapolation of the future trajectory of body actions. This is in keeping with the forward bias in recognition memory observed in the representational-momentum paradigm (Freyd, 1983). The extrapolation of motion information from static pictures and the forward distortion of the movement of a target object rely upon a large neural network that includes higher-order prefrontal and parietal areas (Amorim et al., 2000; Rao et al., 2004) but also higher order visual areas such as the MT/MST complex (Kourtzi & Kanwisher, 2000; Senior et al., 2000). Studies in humans (Krekelberg et al., 2005) and monkeys (Krekelberg et al., 2003) show that the same populations of cells in extrastriate visual areas code for both implied and real motion. Moreover, MT is activated during mental imagery and perception of actual and implied motion (Slotnick et al., 2005). It is possible that mental imagery of forward motion paths (Munger et al., 1999) allows us to fill in the missing visual information and thus to create representational momentum effects. Previous research about the neural underpinnings of implied-motion perception did not distinguish between biological and non biological

motion. However, studies indicate that observation and imagery of human body movements not only activate visual areas but also neural structures typically involved in motor planning and execution of the very same actions (Fadiga et al., 1999; Fourkas et al., 2006; Iacoboni et al., 1999; Porro et al., 1996) that are part of the mirror neuron system. Mirror neurons respond to either self-produced or observed actions. Importantly, these neurons continue to respond also when the final phase of the action is occluded from sight but can be guessed by the observing monkey (Umiltà et al., 2001). Moreover, motor activation in humans has been found in response to symbolic cues signalling an upcoming movement, thus suggesting a role for the mirror system in predicting and anticipating the actions of other individuals (Kilner et al., 2004). It is also important that activation of the cortico-spinal motor system contingent upon actual observation of grasping movements was modulated by the temporal progress of the observed hand action, with higher motor facilitation during the opening phase (Gangitano et al., 2001). Moreover, the artificial introduction of delayed aperture or sudden closure of fingers suppressed the facilitation of the motor cortex, thus suggesting that mirror mapping is affected by the predictability of the sequence of observed movements (Gangitano et al., 2004).

4. Neural substrates of action and body form representation.

The previous study demonstrated similar neural activations during passive observation of dynamic videos and that of static images of body parts merely implying motion.

However, motor cortex facilitation during static images of body parts that imply an action needs two preliminary processes to occur:

- 1) extraction of the future postures of the action.
- 2) visual recognition of the object that is observed (i.e. the body, otherwise no prediction of the motion can be inferred).

Below I introduce some neural mechanisms thought to be at the basis of these processes.

5. Premotor cortices role in action anticipation.

Monkeys' premotor mirror neurons are activated even in the absence of direct observation of the interaction between the experimenter hand and the grasped object (Umiltà et al., 2001). The interaction between hand and objects may be thought as the end phase, or the goal, of a grasping movement. In the study of Umiltà and colleagues, animals were presented with a fully visible action of the experimenter performing a grasping movement and a critical condition in which the final part of the same action was hidden by an opaque screen, thus occluding the vision of the crucial hand-object interaction. Results showed that the large majority of recorded neurons were activated in the absence of full vision of the action. This result supports the proposal that the activity of mirror neurons' is at the base of action recognition (Gallese et al., 1996). In line with the studies on monkeys, TMS experiments in humans have demonstrated that motor cortex facilitation does not exactly couple the phase of the observed action, but rather simulates the goal of the observed action. If a reaching-to-grasp movement is performed with a sudden, unpredictable,

aperture of the fingers, which is not normally performed in this kind of movement, the excitability of the motor cortex does not follow this part of the action (Gangitano et al., 2004). This result seems to be in line with that of Umiltà 2001 on monkeys premotor neurons activity: premotor cortex is anticipating the goal of an action rather than describing its moment-by-moment dynamic. Premotor cortex activity has been observed also during observation of non biological items' sequence in the case that subjects were able to predict the outcome of the sequence (Schubotz & von Cramon, 2002; 2004). Thus, it is proposed that premotor cortex activity is evoked by anticipation of future perceptual states. The motion of the body is a feature completely dissociable from the form of the body through a kind of stimulus called "point-light-display". This stimulus consists of a dozen of point-light attached to the joints of the limbs of an actor that performs some movements in a darkened room (Johansson, 1973). The motion of this kind of impoverished stimuli can be easily distinguished by subjects from random motion and is referred to as biological motion (BM) (Verfaillie, 2000). Moreover BM is sufficient to convey emotional, gender and identity information of the actor (review in Verfaillie, 2000). Observation of BM stimuli with respect to random dot motion activates the posterior part of Superior Temporal Sulcus (STS) (Puce & Perret, 2003). STS activity is not only correlated to BM perception but necessary as interferential rTMS over this area impairs BM discrimination (Grossman et al., 2005). As said above, beside temporal areas, BM perception through point-light-displays also modulates the activity of frontal areas as Inferior Frontal Gyrus (Saygin et al., 2004) and these activations have been attributed to firing of mirror neurons. It is relevant to underline here that these activations seem to be insensitive to actor morphological identity as the form of the body is absent within point-light-displays.

6. Ventral and dorsal visual stream.

Visual processing and its neural organization in perception are among the most studied issues in cognitive neuroscience. Evidences from monkey and human studies have shown that the visual system separately processes form and motion information (Mishkin, et al., 1983). The ventral stream, from V1 to anterior inferior temporal cortex, is mainly involved in form analysis, while the dorsal stream, from V1 to Superior Temporal Sulcus and Parietal cortex, is involved in motion processing. These two visual pathways have been termed the “what” and “where” visual streams (Mishkin and Ungerleider, 1983). This neurofunctional distinction is thought to be at the basis of different roles of vision in the interaction between animals and their environments. The “where” stream is concerned with the localization of a given object in the environment and guides the orientation and the motor interaction of the animal with it. The “what” stream is concerned with the recognition of the form, shape and low-level features of objects.

Concerning the “what” stream, one of the main problems in visual perception is the consistency of object recognition. Humans are able to perceive and recognize objects from all perspectives and separate complex scenes into organized collection of objects; however the neural mechanisms underlying these ability are unclear. A holistic account for recognition proposes that object identification is based on their global form, that is, objects are perceived as whole shapes rather than as a summation of their parts. Parts- and feature-based models for recognition suggest that object identification begins with the processing of many independent features (or subparts) of the object, which are then followed by an integration process (Robson & Graham, 1981). Evidence accounting for the modular-holistic organization came from the neuropsychological observation of selective impairments in face recognition (Bodamer, 1947). Face processing shows some special neural track as it is more disrupted by inversion (turning the stimulus upside down) than is

object recognition (Yin, 1969). Neuroimaging studies have further characterized the preferential processing of face images highlighting the consistency of neural responses in the Fusiform Gyrus for face images presentation (Haxby et al., 1994; Sergent et al., 1992; Puce et al., 1996; Kanwisher et al., 1997; Kanwisher, 2000).

Beside faces, and among all kind of objects, there is another stimulus category that holds, for many different reasons, a special role in humans' life: the human body. The reasons why this kind of complex stimulus is thought to be important is its social value and the selectivity of the brain structures and processes dedicated to its processing. Body images attract attention and probably gain processing strength as demonstrated by an "inattentional blindness" experiment (Downing et al., 2004). In this experiment participants were required to make a line length judgement on the two arms of a cross. After performing this task for a few trials, an irrelevant stimulus (the "critical stimulus") was presented inside one of the four quadrants of the cross without the participants' knowledge or expectation. A series of studies showed that a substantial number of participants fail to detect simple and high-contrast geometric shapes, but not faces or bodies (Mack & Rock, 1998; Downing et al., 2004). After being alerted to the possibility that something besides the cross would appear, however, participants successfully detect the critical stimulus – demonstrating that the "blindness" seen on the critical trial was due to attention and not a result of perceptual limitations. Body images take precedence over other kinds of critical stimuli showing that the body may be prioritized for attentional selection. This finding is discussed from authors in terms of a perceptual precedence of stimuli that are processed in specialized brain areas.

The perception of human body's form is at the centre of the debate between modular versus distributed organization of the central nervous system (Kanwisher, 2000; Gautier et al., 2000; Haxby et al., 2000). In 2001 Downing et al. discovered a bilateral occipito-temporal visual area, called Extrastriate Body Area (EBA), whose activity is selectively

enhanced during passive observation of headless body images with respect to control non-corporeal complex stimuli (Downing et al., 2001). EBA activity was greater for pictures, sticky drawings and silhouettes of headless whole bodies or non-facial body parts.

Since this first discovery, different other studies have investigated the issue of neural selective responses to body images (Downing et al., 2006; Peelen & Downing, 2005; Peelen et al., 2006). Beside EBA also part of the Fusiform Gyrus (Fusiform Body Area) shows an increase in oxygen metabolism for body images presentation (Peelen & Downing, 2005; Schwarzlose et al., 2005). Given the nature of fMRI technique (i.e. its low temporal resolution and correlational logic), however, it was not possible to infer whether EBA and FBA's activity were necessary to body images discrimination or merely correlated with stimuli processing. While FBA lays in a deep position and is difficult to reach by magnetic pulses, EBA is exposed to the skull and thus easy to stimulate with TMS. EBA location in such an exposed position may also explain the rare observation of neuropsychological deficits in body images recognition. In 2004 Urgesi et al. disentangled this issue by showing that rTMS of EBA disrupts the discrimination of body images and not that of control (motorcycles and faces) stimuli and thus that its activity is necessary to body images processing (Urgesi et al., 2004).

However, given the task and stimuli used in his study, some uncertainty remained on what features of the body is processed in EBA. Indeed, the body simultaneously conveys different kind of information as the morphology of its skin, the form of its structure and the action which it is performing.

Which of these many aspects conveyed by body images is processed in EBA and vPM?

7. Representation of body identity and action in Extrastriate Body Area and ventral Premotor cortex (Study 2).

We designed an event related high-frequency rTMS experiment to test whether EBA activity during body images perception is crucial to code its morphological features, while premotor cortices activity is essential in implied action discrimination.

7.1 Methods.

Participants.

Eighteen healthy individuals (15 women) aged 19-26 (mean 21.3 years) were recruited for the study. Data from one participant were considered as outlier data point and discarded from the analysis because mean latency was higher than three standard deviations from the group mean. Thus, the final sample included seventeen individuals. Fifteen of them were right-handed and two were left-handed according to a standard handedness inventory (Briggs & Nebes, 1975). They were native Italian speakers with normal or corrected-to-normal visual acuity in both eyes and were naïve as to the purposes of the experiment. Information about the experimental hypothesis was provided only after the experimental tests were completed. Participants gave their written informed consent and were paid 15 Euros for their participation in the study. The procedures were approved by the ethics committee of the Fondazione Santa Lucia (Rome) and were in accordance with the ethical standards of the 1964 Declaration of Helsinki. None of the participants had neurological, psychiatric, or other medical problems or any contraindication to TMS (Wasserman, 1998). No discomfort or adverse effects during TMS were reported or noticed.

Stimuli and Tasks.

Two different male models (26, 27 years old) were videotaped while performing four different actions with their right upper or lower limbs. To try and match the movement pattern for each action, the two videotaped models imitated a non-videotaped model placed in front of them. TMS studies demonstrate that observation of real or video actions activates the motor mirror system (Fadiga et al., 2005). Since our design required fast stimuli presentation, we capitalized on our recent report showing motor mirror activation during observation of static images that suggest the perception of body movements (Urgesi et al., 2006a). Therefore, in the present study the sense of acting body was elicited by snapshots depicting the middle phase of specific actions selected from the videotapes of the two models. The different stimuli were matched for the instant at which the snapshot was taken, and for perspective, luminance, and crude contours. The snapshot stimuli were colour pictures modified by means of the Adobe Photoshop software (Adobe Systems Incorporated). For each body part, pairs of stimuli represented meaningful actions (e.g., precision grip vs. gross grasping) or meaningless actions (e.g., foot moving toward the ventral vs. dorsal side of the contralateral knee). To balance the laterality of the stimulus set, the mirror image of each stimulus was presented. Thus, 16 different stimuli per model (8 right- and 8 left-limb) were presented. To rule out any effect of mere observation of graspable objects (Chao et al., 2000; Nelissen et al., 2005) mimicking action stimuli were used in the absence of any object. However, note here that viewing transitive and intransitive actions as well as mimicked actions may activate both left and right ventral premotor cortices (Nelissen et al., 2005; Buccino et al., 2001). In different blocks, participants were given two matching-to-sample tasks. In the first, the matching and the non-matching stimuli depicted two different actions (e.g., backward vs. forward steps) executed by the same model with the same body part (action discrimination task). The second task required the discrimination between two images of exactly the same action

performed by two different models; thus, the matching and non-matching stimuli in the second task differed only for the morphology of body parts (form discrimination task). Crucially, the same set of stimuli was used in the two tasks (Fig. 4a). Thus, any differential effect of extrastriate body area (EBA) and ventral premotor cortex (vPMc) stimulations cannot be due to low-level visual differences in the stimuli. Furthermore, we collected subjective reports of the perceived amount of the motion implied in the matching and non-matching stimuli to rule out that this variable played any role in the experimental effects. After the rTMS session, the experimental stimuli, printed on separate pages, were presented in a counterbalanced order and participants were asked to judge the perceived amount of the motion implied in each image by marking a vertical, 10-cm visual analogue scale (VAS) with 0 cm indicating “no effect” and 10 cm “maximal effect imaginable”. Mean (\pm s.e.m.) intensity score of implied motion for the stimulus set was 5.01 (\pm 0.36), thus confirming that the snapshots actually suggested the perception of implied body actions.

For each pair used in the two tasks, we calculated the absolute value of the difference between the perceived intensity of the motion implied in the two probe stimuli. No significant difference was found between the form (1.47 ± 0.18) and the action discrimination tasks [1.49 ± 0.11 ; $t = -0.17$; $P = 0.868$]. This shows that discrimination of the amount of implied motion cannot account for the dissociation between the two tasks. Therefore, the discrimination performance was arguably based on the representation of action cues in the action discrimination task and on morphological categorization of the acting body in the form discrimination task. ¹⁶

Transcranial Magnetic Stimulation.

Participants wore a tightly fitting bathing cap on which scalp stimulation points were marked. Motor evoked potentials (MEPs) were recorded from first dorsal interosseous (FDI) muscle of the right hand. Surface Ag/AgCl electrodes were placed in a belly-tendon montage with the active electrode placed over the motor point and the reference over the interfalangeal joint. Electromyographic (EMG) signal was amplified at a gain of 1000x by a Digitimer D360 amplifier (Digitimer), band-pass filtered (20 Hz-2.5 kHz) and digitized (sampling rate: 5 kHz) by means of a CED Power 1401 controlled with Spike 2 software (Cambridge Electronic Design). The resting motor threshold (rMT), defined as the lowest intensity able to evoke five out of ten MEPs with an amplitude of at least 50 μ V, was determined by holding the stimulation coil over optimal scalp position (i.e., the motor cortex area contralateral to the right hand producing the largest MEPs) for the FDI muscle. Moreover, during the experimental session EMG signal was continuously recorded from the FDI and from the abductor digiti minimi (ADM) muscles of the responding and non responding hands to control for MEPs that could be evoked by stimulation of vPMc⁸. Off-line visual inspection of the data did not show any MEPs or any alteration of the baseline EMG signal following stimulation of vPMc or EBA on the left or on the right hemisphere with respect to the pre-pulse level of activation. Stimulation sites were identified on each participant's scalp with Softaxic Navigator system (EMS). Skull landmarks (nasion, inion, and two pre-auricular points) and about 60 points providing a uniform representation of the scalp were digitized by means of a Fastrak Polhemus digitizer (Polhemus). Coordinates in Talairach space (Talairach, & Tournoux, 1988) were automatically estimated by the Softaxic Navigator from an MRI-constructed stereotaxic template. The scalp locations that corresponded best to left and right EBA and vPMc coordinates (Downing et al., 2001; Urgesi, et al., 2004; Costantini et al., 2005) were identified and marked with a pen. Mean (\pm s.e.m.) coordinates of the stimulation sites were $x = -53.0 \pm 0.3$, $y = -70.8 \pm 0.4$, $z = 3.5$

± 0.2 for left EBA and $x = 51.9 \pm 0.1$, $y = -72.7 \pm 0.1$, $z = 3.1 \pm 0.2$ for right EBA, corresponding to Brodmann area 37 in the posterior part of the middle temporal gyrus, and $x = -57.3 \pm 0.1$, $y = 11.3 \pm 0.2$, $z = 23.9 \pm 0.1$ for the left vPMc and $x = 57.9 \pm 0.1$, $y = 12.2 \pm 0.2$, $z = 24.2 \pm 0.1$ for the right vPMc, corresponding to Brodmann area 44 in the pars opercularis of the inferior frontal gyrus (Fig. 4c).

We adopted a 2 x 2 x 2 (task x area x hemisphere) factorial design, which included controls for task as well as for stimulation site. Each discrimination task served as control for the other and each target area served as control site for the other. This allowed us to rule out that the experimental effects could be accounted for by differences in task difficulty or by non-specific effect of rTMS on task performance. Our factorial design did not include a sham stimulation condition as baseline because this procedure may not be fully adept to control for a non-specific effect of rTMS. Indeed, several studies have shown that the sensations associated with the coil discharge may induce non-specific shortening of response latencies (Blanke et al. 2005; Marzi et al., 1998; Sawaki et al., 1999; Terao et al., 1997). We planned bilateral stimulation conditions because previous neuroimaging studies have not provided clear-cut evidence for hemispheric lateralization of mirror neuron systems. While some studies show left hemisphere dominance (Hamzei et al., 2003), other studies report bilateral involvement of the two hemispheres in action observation processes (Buccino et al., 2001; Aziz-Zadeh et al., 2006a). Note here that our visual perceptual tasks did not require any semantic categorization of the observed actions or of the acting individuals and, thus, probably did not tap the left hemisphere dominance for language. rTMS was performed by connecting two Magstim Model 200 stimulators with Bistim module (The Magstim Company), producing a maximum output of 1.75 T at the coil surface (stimulus attenuation, 22%; duration, 1 ms; rise time, 110 μ s). Two pulses were delivered with an interstimulus interval of 100 ms by means of a 70 mm figure eight stimulation coil (Magstim polyurethane-coated coil). In keeping with a previous study

showing rTMS suppressive effect on EBA (Urgesi et al., 2004), the first TMS pulse was delivered 150 ms after the onset of sample presentation. The same pulse delay was used for stimulation of EBA and vPMc areas in keeping with magnetoencephalography studies revealing activation of ventral premotor area within 150-200 ms after the visual presentation of moving body parts (Nishitani & Hari, 2000; Nishitani & Hari, 2002). Stimulation intensity was 120% of the rMT for both pulses and ranged from 36% to 84% (mean = 48.4%) of the maximum stimulator output. During stimulation of both EBA and vPMc the coil was held by hand tangential to the scalp, with the handle pointing backward and laterally at a 45° angle from the middle sagittal axis of the participants' head. The position of the coil with respect to the marks was checked continuously. During stimulation, participants wore commercial earplugs to protect their hearing. None of the participants reported phosphenes or muscular twitches after rTMS of EBA and vPMc.

Procedure.

Each participant was tested in a single experimental session lasting approximately 2 hr. The action and form discrimination tasks were presented separately with a block design, and the order of task administration was counterbalanced across participants. A short rest was allowed before proceeding to a different task. For each task, participants completed a sixteen-trials practice block before proceeding to the experimental blocks. During the experimental session, two blocks of eight trials were presented in the left and right EBA and vPMc magnetic stimulation conditions, for a total of 64 trials per task. The order of blocks administration was counterbalanced according to Latin square. Participants sat 57 cm away from a 17-inch monitor (resolution, 1024 x 768 pixels; refresh frequency, 99 Hz), where stimuli appeared on a white background and subtended a 9.1° x 9.1° square region around the fovea. Stimulus-presentation timing, rTMS-triggering, and randomization were

controlled by custom-made software created using Matlab (The MathWorks Inc.) and the Psychophysics Toolbox extensions (Brainard et al., 1997). During the experiment, all participants had their chin and forehead restrained and their head aligned with the centre of the viewing screen. Eye position was monitored and fixation was checked continuously during tachistoscopic presentation by means of a rear view mirror. A trial started with the presentation of a central fixation point lasting 500 ms. The sample stimulus was presented for 150 ms at the center of the monitor. Image persistence was limited by presenting a random-dot mask ($9.1^\circ \times 9.1^\circ$ in size; duration, 500 ms) obtained by scrambling the corresponding sample stimulus by means of a custom-made image segmentation software. Immediately after the disappearance of the mask, the two probe stimuli appeared and remained on the screen until a response was made (Fig. 4b). Participants were asked to respond as quickly as possible by using their index or middle finger to press the left or the right key, respectively, on a custom-made response box. Importantly, the instruction was identical in the two tasks so that any differential modulation of rTMS on a given task was likely to occur at an entirely implicit level. Each key corresponded to one of the two positions on the screen on which the probe stimuli were presented; the position of the probe stimuli was randomized in each trial. Half of the participants responded with their left hand and the other half with their right hand. RTs and accuracy were automatically recorded and stored for analysis.

Data Handling.

For each task, individual mean percentages of correct responses and RTs were separately calculated for each stimulation site (16 trials per cell). Only RTs of correct responses were considered; moreover, RTs that fell below or above three standard deviations from each individual mean were identified for each cell and removed as outliers (2.2% of the total)

(Ratcliff, 1993). Preliminary analyses showed that the interferential effect of left and right EBA and vPMc stimulations was independent from the responding hand; thus, the between-subjects effect of responding hand was not included in the main analyses. Moreover, visual inspection as well as statistical analysis of the data distributions (Shapiro-Wilk test for normality) confirmed normality (in all conditions: $W > 0.92$; $P > 0.179$). RTs and accuracy data were submitted to a three-way ANOVA with task (form or action discrimination), area (EBA, vPMc) and hemisphere (left, right) as within-subjects variables. Post-hoc multiple comparisons were carried out using the Newman-Keuls test.

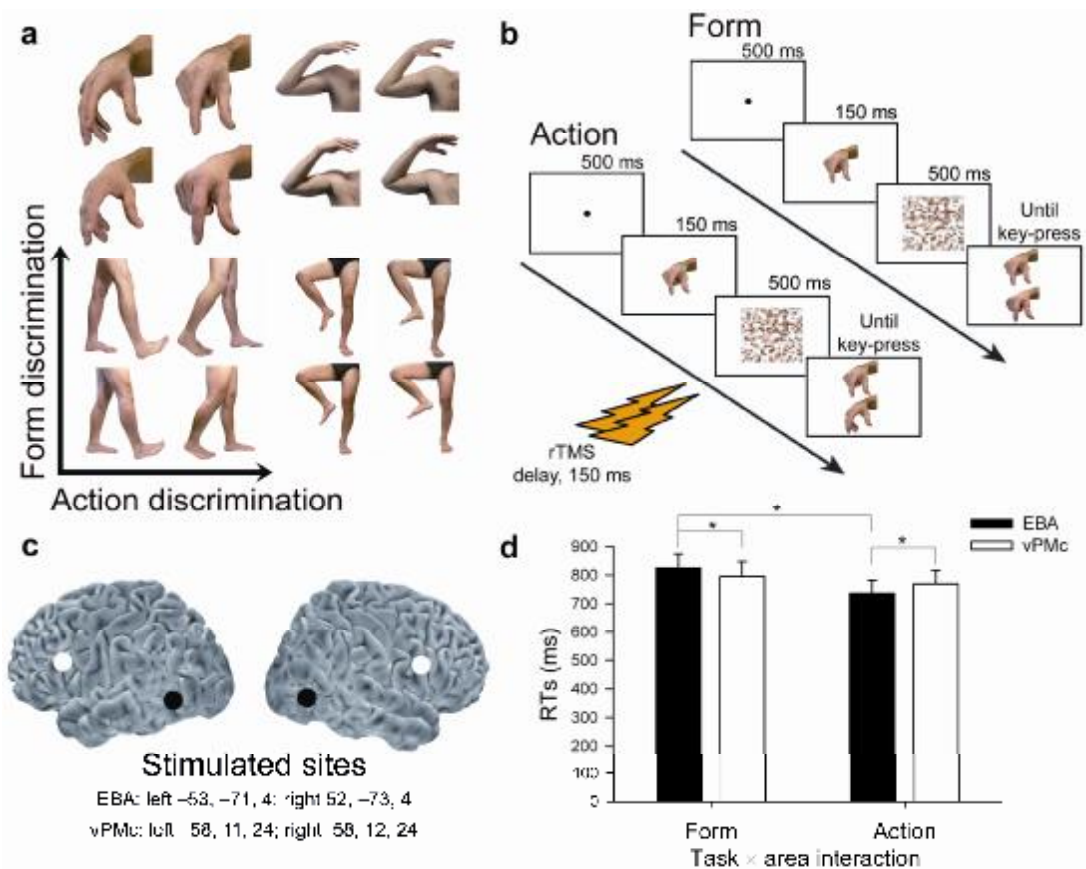


Figure 4. Experimental design and results. (a) Stimuli, (b) time line, and (c) stimulation sites plotted on the standard brain. (d) Mean (\pm s.e.m.) reaction times (RTs) for action and form discriminations after stimulation of EBA and vPMc. $*P = 0.05$.

7.2 Results.

A three-way repeated-measures ANOVA on reaction times with task (action, form), area (EBA, vPMc) and hemisphere (left, right) as within-subject variables showed a significant interaction between task and area [$F(1,16) = 11.84, P = 0.003$; Fig. 4d]. Newman-Keuls post hoc comparisons demonstrated that reaction times for form discriminations were higher after rTMS of EBA ($825.88 \text{ ms} \pm 48.6 \text{ ms}$) than after rTMS of vPMc ($796.11 \text{ ms} \pm 51.19 \text{ ms}, P = 0.036$), showing selective interference of EBA stimulation with the discrimination of bodily forms. In marked contrast, reaction times for action discrimination were higher after rTMS of vPMc ($769.25 \text{ ms} \pm 45.49 \text{ ms}$) than after rTMS of EBA ($735.81 \text{ ms} \pm 47.37 \text{ ms}, P = 0.021$), showing selective interference of vPMc stimulation with the discrimination of bodily actions. As would be expected based on the significant main effect of task [$F(1,16) = 5.69, P = 0.03$], action discrimination was faster than form discrimination after EBA rTMS ($P = 0.001$) and after vPMc rTMS ($P = 0.055$). No other main effects or interactions were significant. Notably, the interference caused by EBA and vPMc stimulation was independent of the hemisphere stimulated (three-way interaction $F(1,16) < 1$; Fig. 5a). This suggests the absence of hemispheric dominance in purely visual discriminations of acting bodies that do not require semantic categorization of actions. Although participants were faster and more accurate [main effect task $F(1,16) = 25.12, P = 0.001$] for action than for form discrimination, the differing difficulty of the tasks cannot explain the reported double dissociation. Indeed, whereas EBA rTMS selectively impaired the ability to discriminate two different forms, vPMc rTMS selectively impaired the ability to discriminate two different actions. Stimulation had no effect on accuracy of responses [task X area $F(1,16) < 1$; Fig. 5b], ruling out any speed-accuracy trade-off. Thus, the present data clearly show that EBA is crucial in processing bodily forms but not bodily actions; the opposite holds true for vPMc.

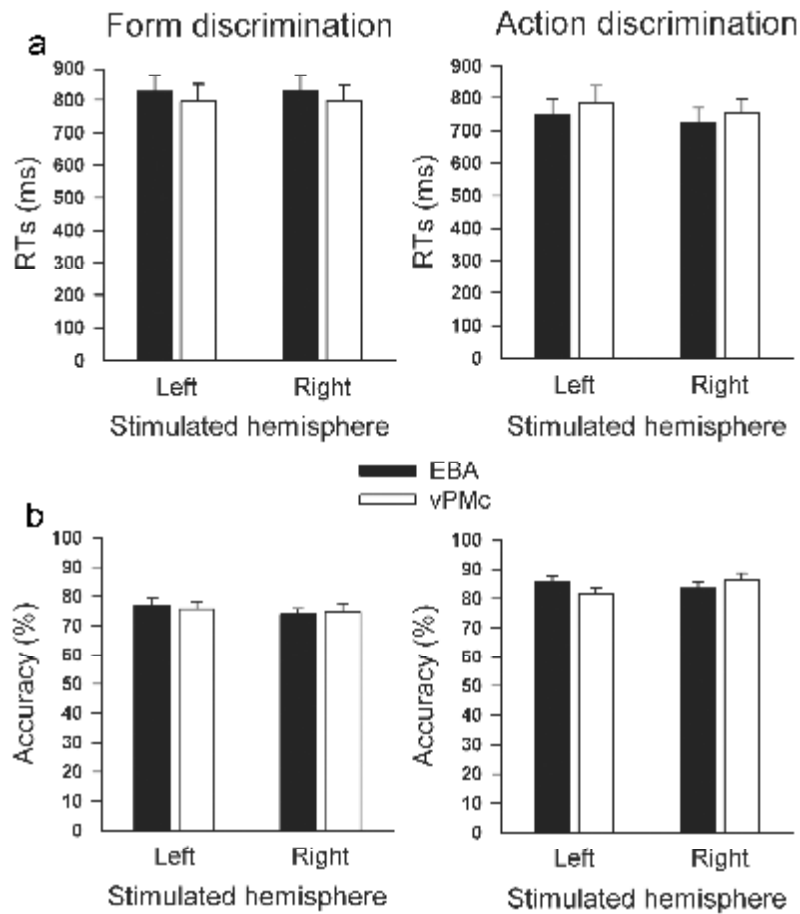


Figure 5. Absence of modulation by hemisphere stimulated. (a) Mean (\pm s.e.m.) reaction times (RTs) and (b) accuracy for action and form discrimination after stimulation of right and left EBA and vPMc.

7.3 Discussion.

Studies showed that EBA is sensitive to the perspective from which bodies are viewed (Chan et al., 2004; Saxe et al., 2006) but is not affected by distortions of the action sequence (Downing et al., 2006). Our study significantly expands previous research by suggesting that EBA is causatively involved in mapping morphological features of human bodies. This function may be fundamental for keeping constant the identity of others even

when body configurations change enormously and at very fast rates during action. Thus, EBA may be crucial for the identification of actors, particularly when facial cues are unavailable or ambiguous. Furthermore, EBA may receive modulatory signals from sensorimotor systems (Astafiev et al., 2004) and thus be involved in the multimodal representation of the actors' body identity. Studies reported that rTMS interference with vPMc impairs imitation of observed actions (Heiser et al., 2003) as well as judgment of the weights lifted by a person (Pobric & de Hamilton, 2006), a task that requires the rehearsal of sensorimotor signals concerning the physical effort made by the model. However, direct evidence for involvement of the motor mirror system in purely visual discriminations of actions was still lacking. The present results provide causative evidence that motor representations are necessary for visuoperceptive action discriminations and that vPMc may represent the observed actions without taking into account the actors' identity. Importantly, the extraction of action cues occurs at a completely implicit level, suggesting that specific perceptual contexts automatically trigger body action simulation in motor areas (Wilson et al., 2005). In conclusion, the reported double dissociation suggests that the visual analysis of human body stimuli is based on the automatic division of labour into two cortical systems, with EBA and possibly other body-selective visual areas (Peelen et al., 2006) representing the actors' identity, and vPMc and possibly other nodes of the frontoparietal mirror system mapping the observed action in a neutral format with respect to the identity of the acting bodies.

8. Neural representations of abstract motor knowledge.

The previous study showed the essential role of premotor cortex in action discrimination during passive observation of static body images implying an action and the crucial role of EBA in discriminating the form of the body. Premotor cortices activation is thought to be at the basis of the facilitation of motor cortex excitability during static images of actions (Urgesi et al., 2006a; Gangitano et al., 2004; Candidi et al., 2008). Coherently with these results, a recent study has described simulative-like properties through direct M1 single neurons recording (Tkach et al., 2007).

The discovery of mirror neurons hints at shared representations of actions between the executer and the observer. This mechanisms have been proposed as the physiological mechanisms at the base of motor learning (Buccino et al., 2004; Stefan et al., 2005; Catmur et al., 2007; Fadiga et al., 2005) and action understanding (Gallese et al., 2004). In this latter perspective, to understand the goal of an action one has to map it in his/her motor system (Gallese et al., 2004). This account for action understanding is supported by the “shared circuits theory” (Keysers et al., 2006). This theory proposes that the same brain areas involved in the first person perspective (I do or I feel) are also involved in the third person perspective (she/he does or she/he feels): it is proposed that this sharing transforms what we see other people do or feel into something very well known to us: what we do and feel ourselves. However there is growing evidence that not only passive observation of actions but even referring to actions through language has an effect on motor system activity (Hauk et al., 2004; Tettamanti et al., 2005; Pulvermuller, 2005; Glenberg & Kaschak, 2002; Meister & Iacoboni, 2007; Fisher & Zwaan, 2008; Buccino et al., 2005; Aziz-Zadeh et al., 2006b). This evidence have been interpreted as a proof of embodied or grounded cognition (Barsalou, 2008). While classical cognitive theories propose that semantic knowledge is represented in the brain into amodal systems and considered cognition as a combination of abstract symbols

(Fodor, 2000; Pylyshyn, 1984), grounded cognition theories propose that semantic knowledge is not amodally stored in the brain but that it is grounded into the activity of the brain's modality specific cortices (Barsalou, 2008).

Different evidences in favor of this theory came from experiments showing the effect of simulation in cognition: simulation consists in re-activating modality-specific neural traces of one's own semantic knowledge derived from one's experience with the world (Barsalou et al., 2003; Barsalou, 2008). One of the important implications of the simulation theory, which is a process at the base of grounded cognition (Barsalou, 2008; Barsalou et al., 2003; Decety & Grezes 2006), is that knowledge representation as well as language comprehension are based on reactivating different sensory aspects associated to a concept which have been acquired in previous experience with the world. Behavioural, neurophysiological and imaging studies indicate that listening to words (Oliveri et al., 2004), verbs (Buccino et al., 2005) and sentences (Glenberg & Kaschak, 2002) that convey motor information activates motor and premotor cortices in a rapid, automatic and somatotopically organized manner (Barsalou et al., 2003; Hauk et al., 2004; Pulvermuller et al., 2001; Pulvermuller, 2005). Glenberg and Kaschak proposed that the meaning of sentences describing an action is grounded into the motor system (Glenberg & Kaschak, 2002). Thus, processing a concept primarily occurs in neural structures (motor, visual, somatosensory) where linguistics does not bear a predominant role (Barsalou et al., 2003; Havas et al., 2007). Moreover, when language specifies certain properties of an action (e.g. the direction of the movement) the motor system is automatically influenced in its efferent motor commands following an action-sentence compatibility rule (i.e. movements are best executed when in the same direction implied by the verb (Action Compatibility Effect) (Glenberg & Kaschak 2002). A combined neurophysiological and behavioural study demonstrated that passive listening of action verbs inhibits the excitability of the motor cortex region representing the limb involved in the execution of the specific action

(Buccino et al., 2005). Reaction times for semantic judgement were also slower when subjects responded with the limb associated to the verb (Buccino et al., 2005). Since no specific feature of the motor scheme was conveyed by the action verb, no facilitation occurred and an inhibition took place instead. This was interpreted as the result of reciprocal inhibition between different specific motor schemata, and specific muscle activations.

The neural correlates of the interaction between semantic-linguistic knowledge and motor skills has been studied in a recent fMRI experiment (Beilock et al., 2008). The authors showed that the amount of motor experience that experimental subjects had with the described action positively correlated with their dorsal premotor cortex activity, while negatively correlated with their sensorimotor primary cortices activity during reading of action related sentences. These results are in line with other experimental evidences demonstrating lower motor involvement during the execution of skilled action with respect to premotor activity which is thought to be at the basis of action selection (Grafton & de C Hamilton, 2007; Rizzolatti & Luppino 2001; Schluter et al., 1998). The conclusion that the authors of this study draw is that motor experience in a given domain increases linguistic processing by activating the same neural processes active during the selection of the motor plan to execute the described action. Thus, “embodying” the described action in ones’ own premotor activity is proposed to be part of the process of language understanding.

The interaction between motor abilities that a person has and the neural mechanisms that are activated by action observation have been shown in imaging studies (Buccino et al., 2004; Calvo-Merino et al., 2004; 2006). These studies showed that motor expertise in a given movement is reflected in higher premotor and parietal areas activation during observation of that specific movement with respect to observation of movements with which the person does not have direct experience or any particular skill. A recent physiological study further described the role of these motor activations during observation

of skilled actions (Aglioti et al., 2008). In expert basket player, the modulation of cortico-spinal excitability during observation of video clips of an athlete shooting at the basket predicted the outcome of the throw: motor evoked potential recorded from the wrist muscle (i.e. the one that is critical in determining the outcome of the shot) were selectively facilitated for out throws in expert athletes with respect to expert watchers and novices. Beyond language, another form of semantic knowledge concerns the definition of a person's attributes. Attribution of motor skills to a given athlete is based on semantic knowledge that defines the persons' identity (Macrae et al., 2000). Serial and parallel models of semantic knowledge activation have been proposed for identity recognition (Bruce & Young 1986; Burton & Bruce 1992) and there is experimental evidence that supports the notion that amongst the traits that are automatically activated when one views a famous person, is the person's profession (cf. Bodenhausen & Macrae, 1998). Specifically, Young and colleagues have shown that RT's in a semantic categorization task based on occupation, are faster than those of a semantic categorization task based on people naming (Young et al., 1988).

It has been shown that knowledge concerning the motor skills of a recognized athlete has an effect on motor reactivity (Bach & Tipper, 2006). Bach and Tipper reported that the participants' response in a recognition task was slower when performed with the limb associated to the domain of motor expertise of the observed athlete. This effect was found either if the athlete was viewed in his sport context or in everyday context. The authors propose that when subjects possess knowledge of the observed model's expertise, this is reflected in the motor system of the observer. These behavioral data confirm the existence of an abstract representation of actions conveyed by identity attribution. Hence, representation of the identity of an expert athlete seems to automatically recruit motor system neural functioning.

One of the major critiques to grounded cognition theories concerns the nature of the activity occurring in modality specific cortices during “abstract cognition” (Mahon & Caramazza, 2008). In the case of motor cortex involvement in identity recognition, the question is whether this activity is necessary for motor knowledge representation or if it is just corollary to other basic processes taking place elsewhere. Some authors have proposed, for example, that language meaning is based on activating mirror neurons from a subset of areas that are active during action observation (Meister & Iacoboni 2007; Buccino et al., 2005).

However the neurophysiological origin of this abstract “identity-related” representation of motor skills is still unknown.

We performed two single pulse TMS study on motor cortex excitability of arm and leg muscles to test whether the association of motor skills to athletes has an effect on motor cortex excitability and if this modulation is based on mirror neurons activity.

9. Grounding the skills of a motorically expert model in the cortico-spinal system of a (naïve) onlooker (Study 3).

In sum, abstract motor representation and action simulation (direct action observation) seem to represent two independent processes that contribute to inhibitory and facilitatory phenomena, respectively. In the present study, we aim to test two predictions:

- 1) categorizing the identity of an athlete is a form of abstract motor representation and should thus be automatically reflected in the inhibition of the excitability of the observers' motor cortex,
- 2) dominance of categorization in relation to simulation processes should lead to an inhibition; dominance of simulation processes in relation to categorization processes should lead to a facilitation; and equal dominance of both processes would lead to the cancellation of both inhibition and facilitation.

In order to test these predictions we carried out two single-pulse (s-p) TMS experiments. Indeed, although s-pTMS cannot study metabolism modulations of brain networks (as given by imaging techniques), it allows for the study of the direction (inhibition/facilitation) of the effects of experimental manipulations not only at the limb level but also at the muscle level. To test our first prediction we used s-pTMS to measure motor cortex excitability during categorization of the identity of tennis and soccer athletes in “face” and “name” stimuli (Experiment 1). To test the second prediction we used s-pTMS to measure motor cortex excitability during categorization of the identity of tennis and soccer athletes in “in context” implied action images (Experiment 2).

9.1 Methods.

Experiment 1.

Participants.

Thirteen healthy subjects (all males, mean age $25.0 \pm SD 6.5$ years,) participated in this experiment. All subjects except one were right-handed according to the Standard Handedness Inventory (Briggs & Nebes, 1975) and had normal or corrected-to-normal visual acuity. All subjects gave their written informed consent prior to their inclusion in the study and were naïve as to its purpose. Subjects were compensated for their time and specific information concerning the study was only provided after the subject had finished all experimental sessions. The experimental procedures were approved by the Fondazione Santa Lucia ethics committee and were carried out in accordance with the principles of the 1964 Helsinki Declaration. None of the participants had a history of neurological, psychiatric, or other medical problems or any contraindication to TMS (Wasserman, 1998). No discomfort or adverse effects during TMS were noticed or reported. To be included in this experiment each participant had to recognize the identity of all the famous athletes portrayed in a series of face and name stimuli.

Electromyographic (EMG) and TMS recording.

EMG recording was performed with a Viking IV (Nicolet Biomedical, Madison, WI) electromyograph. EMG signal was band-filtered (20 Hz – 2.5 kHz, sampling rate 10 kHz), digitalized and stored for off-line analysis. Pairs of Ag/AgCl surface electrodes (1 cm diameter) were placed over the muscle belly (active electrode) and over the associated joint or tendon (reference electrode) in a classical belly-tendon montage. The ground electrode was placed over the knee for Tibialis Anterioris/Soleus (TA/SOL) and over the dorsal part of the elbow for Extensor Carpi Radialis/Flexor Carpi Radialis (ECR/FCR) recordings. Leg and arm

muscle activity was recorded in different experimental blocks. We recorded from agonist/antagonist muscles of both limbs to specifically control for the muscle specificity of any modulatory effects of the different observation conditions. TMS of ECR/FCR was performed using a 70 mm figure-of-eight coil connected to a Magstim Super Rapid Transcranial Magnetic Stimulator (The Magstim Company, Carmarthenshire, Wales, UK) placed over the left motor cortex. The coil was held tangentially to the skull with the handle pointing 45° away from the nasion-inion line in a postero-lateral direction (Brasil-Neto et al., 1992; Mills et al., 1992). As to the TA/SOL muscles, motor cortical representation is placed deep along the interhemispheric sulcus and difficult to reach with the magnetic pulse, a circular coil was used to stimulate the leg muscles. To find individual optimal scalp positions (OSP, i.e. the stimulation position that induces Motor Evoked Potentials of maximal amplitude) for each muscle, the coil was moved in steps of 1 cm over the motor cortex and the OSP was marked on a bathing cap worn by the subjects. Once the OSP was found the resting Motor Threshold (rMT) was defined as the lowest intensity of stimulation that produced five MEPs out of ten consecutive magnetic pulses with at least 50 μ V of amplitude. We defined the rMT by targeting the ECR (using the figure of eight coil for the upper limb) and TA (using the conic coil for the lower limb) antigravity muscles. TMS studies in which two muscles are recorded simultaneously (like in this study ECR/FCR and TA/SOL), determined rMT by targeting muscles presenting a higher threshold to avoid that any differential modulations involving the less excitable muscle were lost (Romani et al., 2005; Fourkas et al, 2006). Here we chose the lower threshold muscle to allow using stimulation intensities 20% above rMT without saturating the stimulators also in subjects with high thresholds. Importantly, the chosen scalp positions allowed us to record a clear and stable simultaneous EMG signal (ten MEPs out of ten TMS pulses) from FCR during ECR stimulation and from SOL during TA stimulation (Krings et al., 1998). Mean rMT was $67.3 \pm \text{SD } 9.46 \%$ for TA and $55.8 \pm \text{SD } 10.17 \%$ for ECR. Single pulses TMS with 120% intensity of individual rMT were delivered

over the OSP muscles'. EMG recording started 100 ms before magnetic pulse delivery. It was thus possible to control for the absence of muscular pre-activation in each trial. Motor evoked potentials (MEP) peak-to-peak amplitudes (in milliVolts) were collected and stored on a computer for off-line analysis.

Visual stimuli.

The experimental visual stimuli consisted in the last name of five famous tennis and five soccer players and the faces of the same athletes. Stimuli sustained a visual angle of about 9.3 degrees and were effortlessly perceived by participants. The experimental stimuli are shown in Fig. 6.



Figure 6. Athletes names and faces (*Experiment 1*) are shown in the upper part of the figure, “in action” full-body images of the same athletes (*Experiment 2*) are show in the lower part of the figure.

Procedure.

Participants were tested in two sessions of approximately 90 min each. Each session concerned recording from either arm (simultaneously from ECR/FCR) or leg (simultaneously from TA/SOL) muscles. The stimulation order of the upper and lower limbs was counterbalanced across subjects. During the experimental blocks, the subjects were

comfortably seated in a dimly lit room at a distance of 80 cm in front of a computer screen (SONY Trinitron CPD-E400P, 60 Hz refresh rate).

Each session consisted of two experimental blocks of 30 trials. Before starting the experiment, subjects were instructed to pay attention to the visual stimuli presented on the screen and to verbally categorize the stimuli (saying "soccer player" or "tennis player") during each inter-trial interval (ISI). During each experimental block participants were presented with 5 tennis and 5 soccer stimuli repeated three time each. Thus, 30 MEPs per block were obtained (15 MEPs per condition). Name and face stimuli were presented in separate blocks counterbalanced for each limb and across subjects. Each stimulus appeared at the centre of the screen for 1500 ms. During the stimulus presentation, a single pulse of TMS was delivered over the subjects' muscle OSP at 120% of rMT. The magnetic stimulation was delivered at random times ranging between 1100 and 1400 ms from stimulus onset to avoid any priming effects that could affect MEP amplitude (Fig. 7). TMS frequency during experimental blocks was < 0.1 Hz so as to avoid that TMS *per se* might influence motor cortex excitability (Chen et al., 1997).

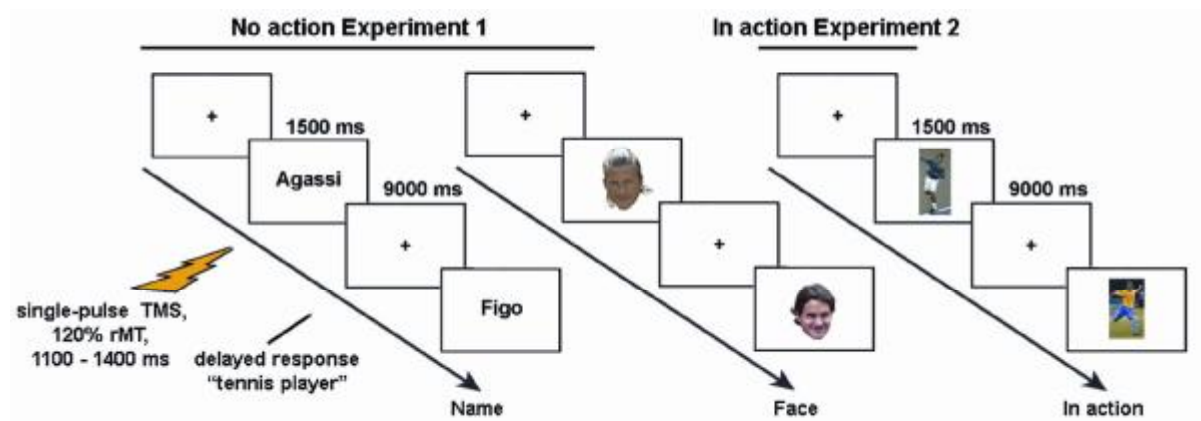


Figure 7. Examples of typical event trials for “name” and “face” (Experiment 1) and “in action” (Experiment 2) blocks.

Data handling.

MEP amplitudes that fell above or below 3 standard deviations, from each individual mean for each experimental condition, were excluded as outliers (9.85 % of total, 1.14 MEP for each subject).

Raw MEPs amplitudes were entered in a (2 x 2 x 2 x 2) factorial design with Stimulus (Face, Name), Sport (Soccer, Tennis), Limb (Arm, Leg), and Muscle (ECR/TA vs. FCR/SOL) as main effects. Post-hoc comparisons were performed with Newman-Keuls test.

9.2 Results Experiment 1.

MEP amplitude analysis showed a main effect of Limb factor ($F_{1,12}=26.467$) with arm muscles ($1.112 \pm \text{SD } 0.588$ mV) being more excitable than leg muscles ($0.712 \pm \text{SD } 0.459$ mV $p=0.000$). The Muscle factor also reached significance ($F_{1,12}=9.486$) because MEP amplitudes were significantly higher because ECR/TA ($0.983 \pm \text{SD } 0.517$ mV) compared to FCR/SOL ($0.841 \pm \text{SD } 0.599$ mV $p=0.009$). This may be due both to the fact that OSP for the former muscles was used and to their larger cortico-spinal representation. Importantly the only interaction that resulted significant was the one between Sport and Limb ($F_{1,12}=24.412$ $p=0.000$) (Fig. 8). Post-hoc comparisons showed that the upper limb was inhibited during the presentation of tennis stimuli ($1.090 \pm \text{SD } 0.599$ mV) with respect to soccer stimuli ($1.132 \pm \text{SD } 0.581$ mV; $p=0.013$). The opposite pattern of relative inhibition was observed for leg muscles which were selectively inhibited during the categorization of soccer stimuli ($0.683 \pm \text{SD } 0.457$ mV) but not during the categorization of tennis stimuli ($0.742 \pm \text{SD } 0.466$ mV $p=0.000$). No other main effect or interaction resulted significant (all $p>0.9$).

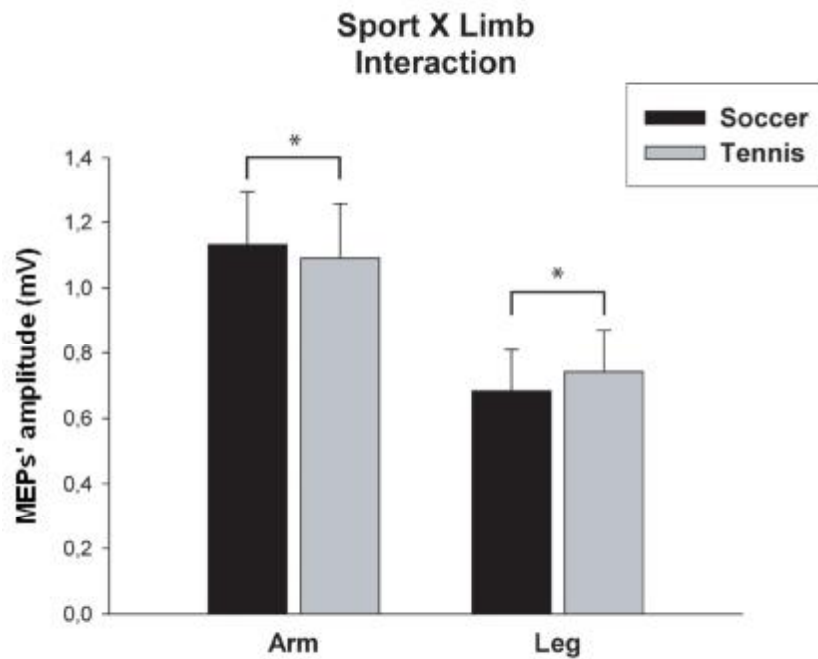


Figure 8. *Interaction of Sport and Limb factors. Raw amplitude in mV (mean \pm S.E.M.) of MEPs recorded from arm (ECR/FCR) and leg (TA/SOL) muscles. Histograms show that arm muscles are more inhibited during ‘tennis player’ than ‘soccer player’ stimuli presentation. The opposite pattern was found for leg muscles (all p s < 0.013459). The difference between arm and leg is likely to be due to the larger cortico-spinal motor representation of arm muscles.*

The significance of the interaction between Sport and Limb factors when comparing raw MEP amplitudes indicates that the pattern of relative inhibition of the limb muscles associated to the sport is independent from MEP absolute amplitude. However, to further confirm the robustness of the result we performed the same analysis on z-normalized scores that allowed to compare MEPs recorded from each muscle independently from their absolute amplitude. Raw MEPs were normalized on the individual grand mean of each muscle ($z = [(single\ mean) - (muscle's\ grand\ mean\ in\ all\ experimental\ conditions)] / muscle's\ standard\ deviation\ in\ all\ experimental\ conditions$). Again, the Sport by Limb interaction was significant ($F_{1,12}=22.972$ $p=0.000$). Post-hoc tests revealed that the upper limb was inhibited during the observation of tennis items ($z=-0.066 \pm SD\ 0.989$) with respect to soccer items ($z=0.037 \pm SD$

0.991 $p=0.032$) while lower limb muscles were inhibited during the observation of soccer items ($z=-0.037 \pm SD 0.988$) with respect to tennis items ($z=0.066 \pm SD 1.005$ $p=0.014$) (Tab.1). No other main effects or interactions between factors were significant ($p>0.124$).

NAME – FACE (Experiment 1)	UPPER LIMB	LOWER LIMB
TENNIS	- 0.036 \pm SD 0.987	0.066 \pm SD 1.005
SOCCER	0.036 \pm SD 0.990	- 0.066 \pm SD 0.989

Table 1. Mean z -normalized MEPs amplitude \pm SD for Upper (ECR/FCR) and Lower (TA/SOL) limb muscles during tennis and soccer face and names images presentation (Experiment 1).

Values refer to the interaction between Sport and Limb factors (Experiment 1). This normalization allows the comparison of arm and leg muscles and shows the relative inhibition of arm muscle cortical excitability for tennis stimuli presentation and the reverse pattern for leg muscles ($p < 0.031782$).

9.3 Experiment 2.

We chose full body “in action” images of the same ten athletes presented in Experiment 1. The images portrayed the athletes performing a “typical” sport movement (examples in figure 1, right post part). The tennis racquet and soccer ball were removed from the images as these tools might facilitate the excitability of the motor system (Chao & Martin, 2000; Beauchamp et al., 2002). The implied motion in each image was controlled for by asking ten independent participants to rate along a Visual Analog Scale the motion implied in a set of 20 tennis and 20 soccer still images. Subjects rated the implied motion of each image by marking a x-cm

vertical Visual Analog Scale. The upper and the lower extremity of the VAS indicated ‘maximal implied movement’ and ‘no implied movement’, respectively. Participants were explicitly asked to rate the motion implied in the entire body, lower limbs and upper limbs in separate blocks the order of which was counterbalanced. Based on the subjective ratings of implied motion a subset of 5 images for each sport was selected.

The same 13 subjects of Experiment 1 underwent Experiment 2 in a separate testing session performed the same day. The order of the experiments was counterbalanced across subjects. The experimental procedures and data handling were identical to those of Experiment 1, exception made for the stimuli used (see Fig. 7, rightmost part).

9.4 Results Experiment 2.

The subjective ratings of the motion implied in “In action” sport snapshots were compared using a two-way (3 X 2) repeated measures “within subjects” ANOVA with factors Part of the body (whole body, lower limb, upper limb) and Sport (tennis, soccer). No main factor reached statistical significance ($p > 0.08$). The interaction between Part of the body and Sport was significant ($F_{2,18} = 38.42$, $p = 0.000$) and revealed that the implied motion in the upper limb was higher for tennis ($72.060 \pm \text{SD } 14.787$ cm) compared to soccer images ($49.180 \pm \text{SD } 11.732$ cm, $p = 0.000$). Conversely, the implied motion in the lower limb was higher for soccer ($70.900 \pm \text{SD } 14.282$ cm) compared to tennis images ($43.840 \pm \text{SD } 9.858$ cm, $p = 0.000$). Whole body implied motion did not differ between soccer ($68.820 \pm \text{SD } 15.200$ cm) and tennis ($62.740 \pm \text{SD } 17.566$ cm) stimuli ($p = 0.150$).

The ANOVA on raw MEP amplitudes revealed a main effect of Limb factor ($F_{1,12} = 24.614$, $p = 0.000$) that is explained by the higher excitability of arm ($1.168 \pm \text{SD } 0.564$ mV) with respect to leg muscles ($0.772 \pm \text{SD } 0.548$ mV). The Muscle factor also reached significance ($F_{1,12} = 6.265$, $p = 0.0278$), with ECR/TA muscles being more excitable ($1.046 \pm \text{SD } 0.576$ mV)

than FCR/SOL ($0.895 \pm \text{SD } 0.595 \text{ mV}$). No other factor or interaction was significant (all $p > 0.084$). Importantly, unlike experiment 1 where names and faces of soccer or tennis athletes were used, the interaction between Sport and Limb did not reach significance ($F_{1,12}=0.815$ $p=0.385$) in this experiment where “in action” stimuli were used. Like in Experiment 1, we performed a z-normalization on raw data and ran the same analysis with factors Sport, Limb and Muscle. Again, unlike experiment 1 and in line with the analysis performed on raw MEP amplitude, no factor or interactions between factors reached significance ($p > 0.606$) (Tab.2).

IN ACTION (Experiment 2)	UPPER LIMB	LOWER LIMB
TENNIS	$- 0.033 \pm \text{SD } 0.929$	$- 0.003 \pm \text{SD } 1.036$
SOCCER	$0.033 \pm \text{SD } 1.064$	$0.003 \pm \text{SD } 0.961$

Table 2. Mean z-normalized MEPs amplitude \pm SD for Upper (ECR/FCR) and Lower (TA/SOL) limb muscles during “In action” image presentation (Experiment 2).

No difference between the excitability of arm and leg muscles was observed during “In action” tennis and soccer stimuli presentation (Experiment 2) ($p > 0.605627$).

To test if “In action” stimuli were effective in modulating motor cortex excitability we used a dependent samples *t*-test to compare MEP amplitudes for “No action” items (Name and Face conditions collapsed together) with the “In action” items in context. A clear motor cortex facilitation was detected in the “In action” session ($0.970 \pm \text{SD } 0.511 \text{ mV}$) compared to the Name/Face “No action” session ($0.912 \pm \text{SD } 0.493 \text{ mV}$ $t_{13}=2.392$, $p=0.034$) (Fig. 9).

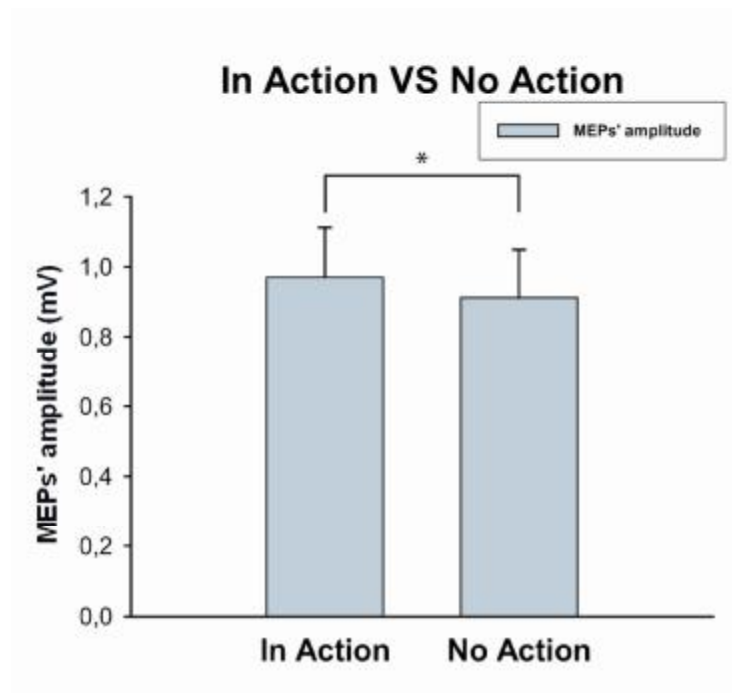


Figure 9. Comparison of raw MEPs amplitude ($mV \pm S.E.M.$) for “In action” (Experiment 2) and “No action” (Experiment 1) stimuli. ‘In action’ stimuli evoked higher MEPs amplitudes ($p=0.033$) than ‘no action’ stimuli thus indicating a general trend towards cortico-spinal facilitation contingent upon implied action observation.

9.5 Discussion.

The main result of the present study is that knowledge of the motor skills of an athlete is reflected in the excitability of the motor cortex of an observer. This phenomenon appears in the form of a somatotopic inhibition of the excitability of the motor cortical representation of both extensor and flexor muscles of the limb associated to the athletes’ domain of expertise. Hence, this representation seems to regard the whole limb associated to the sport rather than a specific muscle. The inhibition of both extensor and flexor muscles of the limb associated to the athletes is cancelled out in the case that the categorization is performed on images implying an action.

The presence of a relative inhibition in both muscles, of each limb, linked to a particular sport, demonstrates that the whole limb was inhibited during categorization. This pattern of inactivation is odd for pairs of agonist-antagonist muscles that are anti-phasic during movement execution: inhibiting both muscles excluded the case that subjects were imagining a specific movement associated with the athletes. In fact, mental motor imagery has proven sufficient to modulate cortico-spinal excitability in a fine-grained fashion (Fourkas et al., 2006; Vargas et al., 2004). The simultaneous inhibition of both agonist and antagonist muscles of the same limb led us to assume a more general representation of the association between athlete category (or motor skills) and the body part related to the sport at which athletes excel. Our results expand previous data (Bach & Tipper, 2005) showing that the impairment of reaction times needed to recognize a given athlete when subjects respond with the associated limb has a cortical origin as the excitability of the cortico-spinal cortex is somatotopically inhibited during the categorization.

This notion may be linked to different sensory and motor aspects (the sensation of the racquet in the hand, the weight of the racquet, the movement necessary to hit the ball) which are coded in a wide neural network (Golberg et al., 2007; Avenanti et al., 2007). Somatosensory stimulation of the hand, arm and leg has facilitatory (Rosenkranz et al., 2003a; Roy et al., 2008) and inhibitory (Rosenkranz et al. 2003b) effects over the amplitude of MEP, demonstrating complex cortico-cortical interactions between motor and somatosensory cortices (Urgesi et al., 2006b). However, single-pulse TMS only gives information about activity occurring between the stimulated cortical site and the muscle from which activity is actually recorded. No direct conclusions can be drawn about the source of this activity; modulation of motor cortex excitability may occur because of inputs coming from other brain structures possibly coding different aspects of an action (Avenanti et al., 2007). Thus, we propose that inhibition, co-occurring with athlete categorization, may derive from activity taking place elsewhere in the brain and feeding into the motor cortex (Tkach et al., 2007).

This result is in line with grounded cognition theories (Barsalou, 2007). One of the major critiques to grounded cognition theories concerns the nature of the activity occurring in modality specific cortices (Mahon & Caramazza, 2008). Specifically, the question is whether this activity is necessary for motor knowledge representation or if it is just corollary to the basic processes taking place elsewhere. In Experiment 2 we investigated whether these inhibitory processes were sensitive to the kind of stimuli that are object of categorization. We attempted to further characterize the nature of the categorization effect by using full body “in action” still images. This kind of stimuli may be considered as compound, conveying both explicit motor information as well as the identity and contextual information about the athlete. Passive action observation automatically activates the motor (Rizzolatti & Craighero 2004) as well as the somatosensory (Fogassi et al 2005; Avikainen et al., 2002; Raos et al., 2004) system of an observer. Premotor and parietal bimodal mirror neurons are at the basis of the simulation of the motor plan and of the somatosensory consequences associated to an observed action (Fadiga et al., 1995; Gangitano et al., 2004; Urgesi et al., 2006a; Avenanti et al., 2007; Costantini et al., 2005). It has been shown that images merely implying an action are capable of activating the motor system (Nishitani & Hari, 2002; 2004; Grezes et al., 2006) and to facilitate motor cortex excitability according to somatotopic rules (Urgesi et al., 2006a). As only the middle phase of action has been shown to be effective in facilitating motor cortex excitability (Urgesi et al., 2006a) we chose images of tennis players portraying the middle phase of a service or forearm shots and images of soccer players depicting the athletes during the act of kicking a ball.

We aimed to study whether the inhibition of motor cortex excitability related to the categorization task would survive the facilitation occurring for action simulation or if, conversely, the inhibition would be diminished or even vanish by the action of simulative facilitating phenomena.

Subjective ratings of the quantity of motion implied in upper and lower limbs were dissociated between tennis and soccer images. This shows, at a minimum interpretation level, that subjects perceived the action of the arm and the leg as “more salient” in tennis and soccer items respectively. However, these judgements were dissociated from the physiological data. In fact we observed a lack of cortical facilitation in arm and leg muscles during viewing of tennis and soccer implied action images, respectively. We suggest that this result is the consequence of the categorization task which necessarily produces an inhibition of the excitability of the same muscles that should have shown a facilitation for implied action simulation. Another possible justification for the observed inhibition effect would be that it represents the undershoot phase of neural activity occurring after an excitatory peak. If this were the case, then it would not be a question of competition between facilitatory simulation and inhibitory categorization, but a question of timing of these processes, their relative interplay, or of differences between the stimulated neural groups. Different motor axons (i.e. axons with different lengths and conductance properties) present different recovery cycles including the undershoot phase of action potential (Kuwabara et al. 2000). Since both the timing and site of stimulation were identical in both Experiment 1 and 2, at least theoretically, we were measuring the same phase of neural firing. Thus, any differences found in the direction of excitation (inhibition or facilitation) between tasks, should derive from a process or processes occurring at the same time, and specific to each task. Moreover, the time window used in the present study derived from our previous experience with implied action facilitatory effects (Urgesi et al., 2006a), further corroborating the independence of timing issues in our results. Moreover, the analysis between “In action” and “No action” stimuli revealed that images portraying athletes during a kicking movement were effective in activating the observers’ motor cortex thus ruling out the possibility that cortical excitability was insensitive to these images at all.

Thus we propose that the effect of inhibiting the motor representation of the limb semantically associated to an athlete always occurs and that it may contrast with simulative (and facilitatory) mirror activity. Simulating an action implied in an image and representing the semantic knowledge associated to sports both compete for motor cortex neural activity virtually at the same time. Interactions between cognitive and motor system functioning have been reported (Redding et al., 1992; Taylor & Thoroughman, 2007). Taylor et al. (2008) varied the cognitive burden of a semantic categorization task showing a reduction of motor adaptation. These authors claim that overlapping neural systems are recruited during early stages of motor learning and categorization tasks. Given that, in our experiments, the categorization task was delayed (i.e. there was a time gap between stimulus presentation and response), our task may have involved cognitive control monitoring processes (Taylor & Thoroughman, 2008) and may have altered cortical reactivity to the action implied in the stimuli (cortical mirror reactivity for action observation has indeed been proposed as the mechanisms for motor learning; Stefan et al., 2005; Catmur et al. 2007; Porro et al., 2007). Specifically, an ERP study comparing simple and delayed responses to stimuli, has shown a more negative deflection elicited by delayed responses, that takes place in a localized region in ACC, possibly related to response inhibition (Qiu et al., 2008).

It is possible that the inhibition found in our study might be due to stimulus response delay rather than being a direct consequence of categorization. Alternatively, if it is a direct consequence of categorization, this might stem from the task's representation properties (i.e. the consciousness of others' identity may inhibit motor cortex activity of the observer (Fadiga et al., 1995)).

Independently of the source of inhibition (which we cannot ascertain given our paradigm), we propose that the categorization task used in this study, is strictly linked to (grounded) motor representations that somatotopically compete with action simulation processes for motor neural resources.

9.6 Conclusions.

In our first experiment we found a specific inhibition of the cortical excitability of the limb associated to the represented categorized sport. We thus confirm that abstract motor representations are automatically reflected into the motor system of an observer. In answer to our first prediction, we conclude that representation of an athlete's motor skills is grounded into the observers' motor cortex, and that this representation is strictly somatotopic.

In our second experiment we found equal dominance of simulation and categorization mechanisms leading to the cancelation of inhibitory and facilitatory processes. This finding supports the idea that inhibitory and facilitatory processes compete for cortical motor resources. We thus propose that these processes depend on simultaneous neural activity, occurring elsewhere in the brain, and flowing into the motor cortex. We have found an inhibition of motor cortical excitability during abstract action representation, confirming previous reports. However, unlike other authors, in our experiments, inhibition processes did not subtend simulative processes.

Hence, our findings seem to better categorize the nature of the neural processes implied in the abstract representation of action.

Owing to the limitations of the TMS technique, some conclusions need to be further explored and supported by use of other imaging techniques. Future developments might include the effort to describe neural activity and its sensitivity to possible interactions between the observer's motor expertise and the degree of knowledge concerning the observed athlete.

10. General discussion.

Isomorphism between ones' own and others' body allows the possibility to simulate the behavior of others by using the same brain areas and neural resources that would be active during the direct experience of a given motor or cognitive state. Simulative mechanisms and mirror neurons activity have been proposed to be at the core of action and emotion understanding (Gallese et al., 2004; Niedenthal, 2007). The ability to understand others' action and emotional states should have an anticipatory nature as we are able to predict the meaning of an action even by watching static images that depict the on-going phase of that action.

In study 1 we demonstrated that the movement implied in static body images is mapped onto the motor cortex of a passive observer. This mechanism follows a somatotopic rule as only the excitability of the muscle that would be involved in action execution is modulated. This modulation takes the form of a facilitation of cortical reactivity which is only induced by phases of the movement in which the action is not ended. This evidence shows the anticipatory nature of the involvement of motor simulative-like mechanisms.

Motor cortex facilitation during action observation may rely on premotor mirror neurons' activity as well as M1 neurons' activity (Tkach et al., 2007). Motor cortex activity for action execution directly feeds into the somatosensory cortex (Cristensen et al., 2005). This mechanisms is thought to be essential in creating anticipatory somatosensory copies of the executed (and eventually observed) action. The coupling of motor and somatosensory copies of an action is at the base of motor learning and may extend to observational motor learning. Indeed, observing an individual that learns a new movement facilitates the acquisition of that motor ability in a passive observer (Mattar et al., 2005). Different contribution of somatosensory and premotor cortices in facilitating simulative-like mechanisms in the motor system have been demonstrated (Avenanti et al., 2007). Future

studies are needed to clarify the contributions of motor and somatosensory anticipatory simulation on action understanding through static images.

Neuropsychological patients, imaging and neurophysiological studies demonstrated the role of focal brain regions in representing specific stimulus categories (Caramazza & Sheldon, 1998). The visual perception of humans' body has been attributed to an occipito-temporal region termed EBA (Peelen & Downing 2007) while the perception of actions activates the premotor node of the mirror neuron system (Rizzolatti & Craighero, 2004). The causal role of these brain regions in representing different features of the body has never been tested.

In study 2 we showed the crucial role of bilateral EBA and ventral Premotor cortices in representing the form of an observed body and the action that the body is performing respectively. Both these mechanisms are thought to be preliminary to the simulation of the action implied in a static image. The present study further characterizes the role of EBA in coding the shape and morphological features of the body. Future studies will try to shed light on EBA's possible role in determining impaired perception of the shape of the body in psychopathological diseases as Eating Disorders. The use of event-related repetitive TMS is thought to create a transient "virtual lesion" of the functionality of a specific brain region allowing the determination of the role of that area in the execution of the task.

Although this impairment is different from that of brain lesions because it is rapid and does not allow plastic changes to compensate for the focal impairment, this approach is useful to guide research in brain damaged patients. Following the results of our Study 2, a recent lesion-mapping study demonstrated that body form and action recognition are impaired for brain lesions centered upon EBA and ventral Premotor cortices respectively (Moro et al., 2008). Further studies are needed to better describe the timing of the integration between visual and motor-simulative mechanisms automatically triggered by observation of the body, and the possible facilitatory effect caused by action simulation on visual perception

of the body (Wilson & Knoblich, 2005; Nikolaev et al., 2008). Different imaging studies have reported modulations of right EBA's activity for allocentric views of body images (Chan et al., 2004; Saxe et al., 2005) and for movement's execution (Astafiev et al., 2004) hinting at possible interactions between visual and sensory-motor systems as mechanisms to distinguish the vision of one's own body and actions with respect to those of others. Recent models concerning the neural mechanisms underlying the cognitive system propose that cognition is grounded into modality specific cortices' activity rather than being amodally stored in the brain (Barsalou, 2008). In this view, motor-related cognition should be embodied into the activity of the motor system.

Study 3 reported the modulation of motor cortex excitability during an identity recognition task performed on famous tennis and soccer athletes. We recorded Motor Evoked Potentials from arm and leg muscles and found a selective inhibition of the excitability of arm and leg muscles during recognition of tennis and soccer player respectively. The link between motor skills attributed to a person and the modulation of the observers' motor cortex excitability is a proof of overlapping systems for action representation and motor-related cognition. The inhibition was observed only in the case that the subjects had to recognize the athletes by their names or faces. Indeed, when the subjects performed the same task on full "in-action" images (that should facilitate the simulation of the observed movement) no modulation of the excitability was measured. We propose that two distinct neural mechanisms occurred in this latter case, possibly resulting in a lack of any modulation of the excitability of the motor cortex: inhibition of the excitability of upper and lower limb for tennis and soccer athletes categorization, and a facilitation of upper and lower limb for tennis and soccer action simulation respectively. Future studies will try to clarify if the inhibition of the excitability of the motor cortex reflects the degree of dexterity attributed to a specific athlete or if it generically defines the category to which the athlete belongs to. Furthermore, if the activity of motor cortices is crucial to recognize an

individual through his motor skills (i.e. motor cortex inhibition is essential in representing the semantic category of “tennis or soccer player”), interfering (behaviourally or physiologically) with motor cortex activity should impair the performance in the categorization task. Another issue that needs further investigation is the role of motor abilities that a person possesses in modulating this semantic “motor-knowledge”.

11. References.

- Aglioti SM, Cesari P, Romani M, Urgesi C. (2008). Action anticipation and motor resonance in elite basketball players. *Nat Neurosci*. 2008 Aug 10. [Epub ahead of print]
- Amorim MA, Lang W, Lindinger G, Mayer D, Deecke L, Berthoz A (2000). Modulation of spatial orientation processing by mental imagery instructions: a MEG study of representational momentum. *J Cogn Neurosci* 12:569 –582.
- Astafiev, S. V., Stanley, C. M., Shulman, G. L., & Corbetta, M. (2004). Extrastriate body area in human occipital cortex responds to the performance of motor actions. *Nature Neuroscience*, 7(5), 542- 548.
- Avenanti A., Bolognini N., Maravita A., Aglioti S.M., (2007). Somatic and motor components of action simulation. *Curr Biol*. 17(24), 2129-35.
- Avikainen S., Forss N., and Hari R., (2002). Modulated activation of the human SI and SII cortices during observation of hand actions. *Neuroimage* 15, 640–646.
- Rao, H., Han, S., Jiang, Y., Xue, Y., Gu, H., Cui, Y., and Gao, D. (2004). Engagement of the prefrontal cortex in representational momentum: an fMRI study. *Neuroimage* 23, 98-103.
- Aziz-Zadeh L, Koski L, Zaidel E, Mazziotta J, Iacoboni M. (2006a). Lateralization of the human mirror neuron system. *J Neurosci*. 26(11):2964-70.
- Aziz-Zadeh L, Wilson SM, Rizzolatti G, Iacoboni M. (2006b). Congruent embodied representations for visually presented actions and linguistic phrases describing actions. *Curr Biol*. 16(18):1818-23.
- Freyd, J.J. (1983). The mental representation of movement when static stimuli are viewed. *Percept. Psychophys*. 33, 575-581.
- Bach P., Tipper S.P., (2006). Bend it like Beckham: embodying the motor skills of famous athletes. *Q J Exp Psychol (Colchester)*. 59(12), 2033-9.
- Baldissera F, Cavallari P, Craighero L, Fadiga L. (2001). Modulation of spinal excitability during observation of hand actions in humans. *Eur J Neurosci*. 13(1):190-4.
- Barsalou L.W., Kyle Simmons W., Barbey A.K., Wilson C.D. (2003). Grounding conceptual knowledge in modality-specific systems. *Trends Cogn Sci.*;7(2):84-91.
- Barsalou L.W. (2008). Grounded cognition. *Annu Rev Psychol*. 59, 617-45. Review.
- Beauchamp MS, Lee KE, Haxby JV, Martin A (2002). Parallel visual motion processing streams for manipulable objects and human movements. *Neuron* 34:149 –159.
- Beilock SL, Lyons IM, Mattarella-Micke A, Nusbaum HC, Small SL. (2008). Sports experience changes the neural processing of action language. *Proc Natl Acad Sci U S A*. 105(36):13269-73.

- Blanke O, Mohr C, Michel CM, Pascual-Leone A, Brugger P, Seeck M, Landis T, Thut G. (2005). Linking out-of-body experience and self processing to mental own-body imagery at the temporoparietal junction. *J Neurosci.* 25(3):550-7.
- Bodenhausen, G.V., & Macrae, C.N. (1998). *Stereotype activation and inhibition*. In: R. S. Wyer Jr. (Eds.), *Advances in social cognition*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc. (Vol. 11, pp.1–52).
- Bodamer, J. (1947). Die prosopagnosie. *Archiv für Psychiatrie und Nervenkrankheiten* 179, 6–53.
- Brainard DH. (1997). The Psychophysics Toolbox. *Spat Vis.* 10(4):433-6.
- Brasil-Neto JP, Cohen LG, Panizza M, Nilsson J, Roth BJ, Hallett M (1992). Optimal focal transcranial magnetic activation of the human motor cortex: effects of coil orientation, shape of the induced current pulse, and stimulus intensity. *J Clin Neurophysiol* 9:132–136.
- Briggs GG, Nebes RD (1975). Patterns of hand preference in a student population. *Cortex* 11:230 –238.
- Brass, M., Bekkering, H., Wohlschläger, A., & Prinz, W. (2000). Compatibility between observed and executed finger movements: comparing symbolic, spatial, and imitative cues. *Brain Cognition*, 44, 124–143.
- Buccino G, Binkofski F, Fink GR, Fadiga L, Fogassi L, Gallese V, Seitz RJ, Zilles K, Rizzolatti G, Freund HJ. (2001). Action observation activates premotor and parietal areas in a somatotopic manner: an fMRI study. *Eur J Neurosci.* 13(2):400-4.
- Buccino G, Lui F, Canessa N, Patteri I, Lagravinese G, Benuzzi F, Porro CA, Rizzolatti G. (2004). Neural circuits involved in the recognition of actions performed by nonconspecifics: an FMRI study. *J Cogn Neurosci.* 16(1):114-26.
- Buccino G, Vogt S, Ritzl A, Fink GR, Zilles K, Freund HJ, Rizzolatti G. (2004). Neural circuits underlying imitation learning of hand actions: an event-related fMRI study. *Neuron.* 42(2):323-34.
- Buccino G., Riggio L., Melli G., Binkofski F., Gallese V., Rizzolatti G., (2005). Listening to action-related sentences modulates the activity of the motor system: a combined TMS and behavioral study. *Brain Res Cogn Brain Res.* 24(3), 355-63.
- Burton AM & Bruce V. (1992). I recognize your face but I can't remember your name: a simple explanation? *British Journal of Psychology*, 83, 45-60.
- Bruce V., Young A. (1986). Understanding face recognition. *Br J Psychol.* 77 (Pt 3), 305-27.
- Calvo-Merino B, Glaser DE, Grèzes J, Passingham RE, Haggard P. (2004). Action observation and acquired motor skills: an FMRI study with expert dancers. *Cereb Cortex.* 15(8):1243-9.

- Calvo-Merino B, Grèzes J, Glaser DE, Passingham RE, Haggard P. (2006). Seeing or doing? Influence of visual and motor familiarity in action observation. *Curr Biol.* 16(19):1905-10. Erratum in: *Curr Biol.* 2006 Nov 21;16(22):2277.
- Candidi M., Urgesi C., Ionta S., Aglioti S.M., (2008). Virtual Lesion of Ventral Premotor Cortex Impairs Visual Perception of Biomechanically Possible but not Impossible Actions. *Social Neuroscience* First published on 16 October. DOI: 10.1080/17470910701676269.
- Catmur C, Walsh V, Heyes C. (2007). Sensorimotor learning configures the human mirror system. *Curr Biol.* 17(17):1527-31.
- Celnik, P., Stefan, K., Hummel, F., Duque, J., Classen, J., & Cohen, L. G. (2006). Encoding a motor memory in the older adult by action observation. *NeuroImage*, 29(2), 677_684.
- Chao LL & Martin A (2000). Representation of manipulable man-made objects in the dorsal stream. *NeuroImage* 12:478–484.
- Chan AW, Peelen MV, Downing PE. (2004). The effect of viewpoint on body representation in the extrastriate body area. *Neuroreport.* 15(15):2407-10.
- Chen R, Classen J, Gerloff C, Celnik P, Wassermann EM, Hallett M, Cohen LG (1997). Depression of motor cortex excitability by low-frequency transcranial magnetic stimulation. *Neurology* 48:1398 –1403.
- Christensen MS, Lundbye-Jensen J, Geertsen SS, Petersen TH, Paulson OB, Nielsen JB. (2007). Premotor cortex modulates somatosensory cortex during voluntary movements without proprioceptive feedback. *Nat Neurosci.* 10(4):417-9.
- Costantini M, Galati G, Ferretti A, Caulo M, Tartaro A, Romani GL, Aglioti SM. (2005). Neural systems underlying observation of humanly impossible movements: an fMRI study. *Cereb Cortex.* 15(11):1761-7.
- Craighero, L., Bello, A., Fadiga, L., & Rizzolatti, G. (2002). Hand action preparation influences the responses to hand pictures. *Neuropsychologia*, 40(5), 492-502.
- Decety J. & Grèzes J. (2006). The power of simulation: imagining one's own and other's Behavior. *Brain Res.* .1079(1), 4-14.
- Di Pellegrino G., Fadiga L., Fogassi L., Gallse V., Rizzolatti G. (1992). Understanding motor events: a neurophysiological study. *Exp. Brain Res.* 91: 176-180, 1992.
- Downing, P. E., Jiang, Y., Shuman, M., & Kanwisher, N. (2001). A cortical area selective for visual processing of the human body. *Science*, 293(5539), 2470–2473.
- Downing PE, Bray D, Rogers J, Childs C. (2004). Bodies capture attention when nothing is expected. *Cognition.* 93(1):B27-38.
- Downing PE, Chan AW, Peelen MV, Dodds CM, Kanwisher N. (2006). Domain specificity in visual cortex. *Cereb Cortex.* 16(10):1453-61.

- Dupont P, Orban GA, De Bruyn B, Verbruggen A, Mortelmans L (1994). Many areas in the human brain respond to visual motion. *J Neurophysiol* 72:1420–1424.
- Iacoboni M, Woods RP, Brass M, Bekkering H, Mazziotta JC, Rizzolatti G. (1999). Cortical mechanisms of human imitation. *Science*. 286(5449):2526-8.
- Fadiga L, Buccino G, Craighero L, Fogassi L, Gallese V, Pavesi G (1999). Corticospinal excitability is specifically modulated by motor imagery: a magnetic stimulation study. *Neuropsychologia* 37:147–158.
- Fadiga L, Craighero L, Olivier E (2005). Human motor cortex excitability during the perception of others' action. *Curr Opin Neurobiol* 15:213–218.
- Fischer MH, Zwaan RA. (2008). Embodied language: a review of the role of the motor system in language comprehension. *Q J Exp Psychol (Colchester)*. 61(6):825-50. Review.
- Fodor J. (2000). *The Mind Doesn't Work That Way*, MIT Press, Cambridge, MA.
- Fogassi L, Ferrari PF, Gesierich B, Rozzi S, Chersi F, Rizzolatti G. (2005). Parietal lobe: from action organization to intention understanding. *Science*. 308(5722):662-7.
- Fourkas AD, Avenanti A, Urgesi C, Aglioti SM. (2006). Corticospinal facilitation during first and third person imagery. *Exp Brain Res*. 168(1-2):143-51.
- Freyd JJ (1983). The mental representation of movement when static stimuli are viewed. *Percept Psychophys* 33:575–581.
- Gallese, V., Fadiga, L., Fogassi, L., and Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain* 119, 593–609.
- Gallese V, Keysers C, Rizzolatti G. (2004). A unifying view of the basis of social cognition. *Trends Cogn Sci*. 8(9):396-403.
- Gangitano M, Mottaghy FM, Pascual-Leone A (2001). Phase-specific modulation of cortical motor output during movement observation. *Neuro-Report* 12:1489–1492.
- Gangitano M, Mottaghy FM, Pascual-Leone A (2004). Modulation of premotor mirror neuron activity during observation of unpredictable grasping movements. *Eur J Neurosci* 20:2193–2202.
- Gauthier I, Skudlarski P, Gore JC, Anderson AW. (2000). Expertise for cars and birds recruits brain areas involved in face recognition. *Nat Neurosci*. 3(2):191-7.
- Glenberg AM, Kaschak MP. (2002). Grounding language in action. *Psychon Bull Rev*. (3):558-65.
- Goldberg R.F., Perfetti C.A., Fiez J.A., Schneider W., (2007). Selective retrieval of abstract semantic knowledge in left prefrontal cortex. *J Neurosci*. 27(14), 3790-8.
- Grafton S, de C Hamilton A (2007) Evidence for a distributed hierarchy of action representation in the brain. *Hum Mov Sci* 26:590–616.

- Grezes, J., & Decety, J. (2001). Functional anatomy of execution, mental simulation, observation, and verb generation of actions: a meta-analysis. *Human Brain Mapping*, 12(1), 1-19.
- Grossman E, Donnelly M, Price R, Pickens D, Morgan V, Neighbor G, Blake R (2000). Brain areas involved in perception of biological motion. *J Cogn Neurosci* 12:711–720.
- Grossman ED, Battelli L, Pascual-Leone A. (2005). Repetitive TMS over posterior STS disrupts perception of biological motion. *Vision Res.* 45(22):2847-53.
- Hauk O, Johnsrude I, Pulvermüller F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron.* 41(2):301-7.
- Havas D.A., Glenberg A.M., Rinck M. (2007). Emotion simulation during language comprehension.. *Psychon Bull Rev.* 14(3), 436-41.
- Haxby JV, Hoffman EA, Gobbini MI. (2000). The distributed human neural system for face perception. *Trends Cogn Sci.* 4(6):223-233.
- Haxby, J. V., Horwitz B, Ungerleider LG, Maisog JM, Pietrini P, Grady CL. (1994). The functional organization of human extrastriate cortex: A PET-fCBF study of selective attention to faces and locations. *J. Neurosci.* 14, 6336–6353.
- Heiser M, Iacoboni M, Maeda F, Marcus J, Mazziotta JC. (2003). The essential role of Broca's area in imitation. *Eur J Neurosci.* 17(5):1123-8.
- Iacoboni M, Woods RP, Brass M, Bekkering H, Mazziotta JC, Rizzolatti G (1999). Cortical mechanisms of human imitation. *Science* 286:2526–2528.
- Jellema T, Perrett DI (2003). Cells in monkey STS responsive to articulated body motions and consequent static posture: a case of implied motion? *Neuropsychologia* 41:1728 –1737.
- Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Percept. Psychophys.*, 14, 201–211.
- Kanwisher, N., McDermott, J. & Chun, M. (1997). The fusiform face area: a module in human extrastriate cortex specialized for face perception. *J. Neurosci.* 17, 4302–4311.
- Kanwisher N. (2000). Domain specificity in face perception. *Nat Neurosci.* 3(8):759-63. Review.
- Kellenbach ML, Brett M, Patterson K (2003). Actions speak louder than functions: the importance of manipulability and action in tool representation. *J Cogn Neurosci* 15:30–46.
- Kilner, J.M., Vargas, C., Duval, S., Blakemore, S.J., and Sirigu, A. (2004). Motor activation prior to observation of a predicted movement. *Nat. Neurosci.* 7, 1299-1301.
- Kourtzi Z, Kanwisher N (2000). Activation in human MT/MST by static images with implied motion. *J Cogn Neurosci* 12:48 –55.

- Krekelberg B, Dannenberg S, Hoffmann KP, Bremmer F, Ross J (2003). Neural correlates of implied motion. *Nature* 424:674–677.
- Krekelberg B, Vatakis A, Kourtzi Z (2005). Implied motion from form in the human visual cortex. *J Neurophysiol* 94:4373–4386.
- Krings T, Naujokat C, von Keyserlingk DG (1998). Representation of cortical motor function as revealed by stereotactic transcranial magnetic stimulation. *Electroencephalogr Clin Neurophysiol* 109:85–93.
- Kuwabara S, Cappelen-Smith C, Lin CS, Mogyoros I, Bostock H, Burke D. (2000). Excitability properties of median and peroneal motor axons. *Muscle Nerve*. 23(9):1365-73.
- Mack, A., & Rock, I. (1998). *Inattentive blindness*. London: MIT Press.
- Macrae C.N., Bodenhausen G.V. (2000). Social cognition: thinking categorically about others. *Annu Rev Psychol*. 51, 93-120. Review.
- Mahon B.Z., Caramazza A., (2008). Concepts and Categories: A Cognitive Neuropsychological Perspective. *Annu Rev Psychol*.
- Marzi CA, Miniussi C, Maravita A, Bertolasi L, Zanette G, Rothwell JC, Sanes JN. (1998). Transcranial magnetic stimulation selectively impairs interhemispheric transfer of visuo-motor information in humans. *Exp Brain Res*. 118(3):435-8.
- Mattar AA, Gribble PL. (2005). Motor learning by observing. *Neuron*. 46(1):153-60.
- Meister IG, Iacoboni M. (2007). No language-specific activation during linguistic processing of observed actions. *PLoS ONE*. 2(9):e891.
- Mills KR, Boniface SJ, Schubert M (1992). Magnetic brain stimulation with a double coil: the importance of coil orientation. *Electroencephalogr Clin Neurophysiol* 85:17–21.
- Mishkin, M., Ungerleider, L. & Macko, K. (1983). Object vision and spatial vision: two central pathways. *Trends Neurosci*. 6, 414–417.
- Moro V, Urgesi C, Pernigo S, Lanteri P, Pazzaglia M, Aglioti SM. (2008). The neural basis of body form and body action agnosia. *Neuron*. 60(2):235-46.
- Munger MP, Solberg JL, Horrocks KK (1999). The relationship between mental rotation and representational momentum. *J Exp Psychol Learn Mem Cogn* 25:1557–1568.
- Nelissen K, Luppino G, Vanduffel W, Rizzolatti G, Orban GA (2005). Observing others: multiple action representation in the frontal lobe. *Science* 310:332–336.
- Nikolaev AR, Ziessler M, Dimova K, van Leeuwen C. (2008). Anticipated action consequences as a nexus between action and perception: evidence from event-related potentials. *Biol Psychol*. 78(1):53-65.

- Nishitani, N., and Hari, R. (2000). Temporal dynamics of cortical representation for action. *Proc. Natl. Acad. Sci. USA* 97, 913-918.
- Nishitani, N., and Hari, R. (2002). Viewing lip forms: cortical dynamics. *Neuron* 36, 1211-1220.
- Oliveri M., Finocchiaro C., Shapiro K., Gangitano M., Caramazza A., Pascual-Leone A., (2004). All talk and no action: a transcranial magnetic stimulation study of motor cortex activation during action word production. *J Cogn Neurosci.* 16(3), 374-81.
- Peelen MV, Downing PE. (2005). Selectivity for the human body in the fusiform gyrus. *J Neurophysiol.* 93(1):603-8.
- Peelen MV, Downing PE. (2005). Within-subject reproducibility of category-specific visual activation with functional MRI. *Hum Brain Mapp.* 25(4):402-8.
- Peigneux P, Salmon E, van der Linden M, Garraux G, Aerts J, Delfiore G, Degueldre C, Luxen A, Orban G, Franck G (2000). The role of lateral occipitotemporal junction and area MT/V5 in the visual analysis of upper-limb postures. *NeuroImage* 11:644–655.
- Pylyshyn, Z.W. (1984). *Computation and Cognition: Toward A Foundation For Cognitive Science*, MIT Press, Cambridge, MA.
- Pobric, G, and de C. Hamilton, A. (2006). Action understanding requires the left inferior frontal cortex. *Curr. Biol.* 16, 524-529.
- Porro CA, Francescato MP, Cettolo V, Diamond ME, Baraldi P, Zuiani C, Bazzocchi M, di Prampero PE (1996). Primary motor and sensory cortex activation during motor performance and motor imagery: a functional magnetic resonance imaging study. *J Neurosci* 16:7688 –7698.
- Porro CA, Facchin P, Fusi S, Dri G, Fadiga L. (2007). Enhancement of force after action observation: behavioural and neurophysiological studies. *Neuropsychologia.* 45(13):3114-21.
- Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology*, 9, 129-154.
- Prinz, W. (2002). *Experimental approaches to imitation*. In A. N. Meltzoff & W. Prinz (Eds.), *The imitative mind: Development, evolution and brain bases* (pp. 143_162). Cambridge, UK: Cambridge University Press.
- Puce A, Perrett D (2003). Electrophysiology and brain imaging of biological motion. *Philos Trans R Soc Lond B Biol Sci* 358:435– 445.
- Puce, A., Allison, T., Asgari, M., Gore, J. C. & McCarthy, G. (1996). Differential sensitivity of human visual cortex to faces, letter strings, and textures: a functional magnetic resonance imaging study. *J. Neurosci.* 16, 5205–5215.
- Pulvermüller F., Härle M., Hummel F., (2001). Walking or talking? Behavioral and neurophysiological correlates of action verb processing. *Brain Lang.* 78(2), 143-68.

- Pulvermüller F. (2005). Brain mechanisms linking language and action. *Nat Rev Neurosci.* (7):576- 82. Review.
- Romani M, Cesari P, Urgesi C, Facchini S, Aglioti SM (2005). Motor facilitation of the human cortico-spinal system during observation of biomechanically impossible movements. *NeuroImage* 26:755–763.
- Qiu J., Li H., Liu Q., Zhang Q., (2008). Brain mechanism of response execution and inhibition: an event-related potential study. *Neuroreport.* 19(1), 121-5.
- Rao H, Han S, Jiang Y, Xue Y, Gu H, Cui Y, GaoD (2004). Engagement of the prefrontal cortex in representational momentum: an fMRI study. *Neuro- Image* 23:98 –103.
- Ratcliff R. (1993). Methods for dealing with reaction time outliers. *Psychol Bull.* 114(3):510-32.
- Redding GM, Rader SD, Lucas DR (1992). Cognitive Load and Prism Adaptation. *J Mot Behav* 24: 238–246.
- Rizzolatti G, Craighero L (2004). The mirror-neuron system. *Annu Rev Neurosci* 27:169 –192.
- Rizzolatti G & Luppino G. (2001) The cortical motor system. *Neuron* 31:889–901.
- Robson, J. G., & Graham, N. (1981). Probability summation and regional variation in contrast sensitivity across the visual field. *Vision Research*, 21, 409–418.
- Roy FD, Gorassini MA. (2008). Peripheral sensory activation of cortical circuits in the leg motor cortex of man. *J Physiol.* 586(Pt 17):4091-105.
- Rosenkranz K, Pesenti A, Paulus W, Tergau F. (2003a). Focal reduction of intracortical inhibition in the motor cortex by selective proprioceptive stimulation. *Exp Brain Res.* 149(1):9-16.
- Rosenkranz K, Rothwell JC. (2003b). Differential effect of muscle vibration on intracortical inhibitory circuits in humans. *J Physiol.* 551(Pt 2):649-60. Erratum in: *J Physiol.* 2003 552(Pt 3):993-5.
- Saygin, A.P., Wilson, S.M., Hagler, D.J. Jr, Bates, E. & Sereno, M.I. (2004). Point-light biological motion perception activates human premotor cortex. *J. Neurosci.*, 27, 6181–6188.
- Saxe R, Jamal N, Powell L. (2006). My body or yours? The effect of visual perspective on cortical body representations. *Cereb Cortex.* 16(2):178-82.
- Sawaki L, Okita T, Fujiwara M, Mizuno K. (1999). Specific and non-specific effects of transcranial magnetic stimulation on simple and go/no-go reaction time. *Exp Brain Res.* 127(4):402-8.

- Schluter N, Rushworth M, Passingham R, Mills K (1998). Temporary interference in human lateral premotor cortex suggests dominance for the selection of movements. A study using transcranial magnetic stimulation. *Brain* 121:785–799.
- Schubotz RI, von Cramon DY (2002). A blueprint for target motion: fMRI reveals perceived sequential complexity to modulate premotor cortex. *NeuroImage* 16:920–935.
- Schubotz RI, von Cramon DY. (2004). Sequences of abstract nonbiological stimuli share ventral premotor cortex with action observation and imagery. *J Neurosci.* 24(24):5467-74
- Schwarzlose, R. F., Baker, C. I. & Kanwisher, N. (2005). Separate face and body selectivity on the fusiform gyrus. *J. Neurosci.* 25, 11055–11059.
- Senior C, Barnes J, Giampietro V, Simmons A, Bullmore ET, Brammer M, David AS (2000). The functional neuroanatomy of implicit-motion perception or representational momentum. *Curr Biol* 10:16–22.
- Sergent, J., Ohta, S. & MacDonald, B. (1992). Functional neuroanatomy of face and object processing: a positron emission tomography study. *Brain* 115, 15–36.
- Slotnick SD, Thompson WL, Kosslyn SM (2005). Visual mental imagery induces retinotopically organized activation of early visual areas. *Cereb Cortex* 15:1570–1583.
- Stefan K, Cohen LG, Duque J, Mazzocchio R, Celnik P, Sawaki L, Ungerleider L, Classen J. (2005). Formation of a motor memory by action observation. *J Neurosci.* 25(41):9339-46.
- Talairach, J. & Tournoux, P. *Co-planar stereotaxic atlas of the human brain* (Thieme, Stuttgart, 1988).
- Taylor JA, Thoroughman KA. (2007). Divided attention impairs human motor adaptation but not feedback control. *J Neurophysiol.* 98(1):317-26.
- Taylor JA, Thoroughman KA. (2008). Motor adaptation scaled by the difficulty of a secondary cognitive task. *PLoS ONE.* 3(6):e2485.
- Terao Y, Ugawa Y, Suzuki M, Sakai K, Hanajima R, Gemba-Shimizu K, Kanazawa I. (1997). Shortening of simple reaction time by peripheral electrical and submotor-threshold magnetic cortical stimulation. *Exp Brain Res.* 115(3):541-5.
- Tettamanti M, Buccino G, Saccuman MC, Gallese V, Danna M, Scifo P, Fazio F, Rizzolatti G, Cappa SF, Perani D. (2005). Listening to action-related sentences activates fronto-parietal motor circuits. *J Cogn Neurosci.* 17(2):273-81.
- Tkach D, Reimer J, Hatsopoulos NG. (2007). Congruent activity during action and action observation in motor cortex. *J Neurosci.* 27(48):13241-50.
- Tootell RB, Reppas JB, Kwong KK, Malach R, Born RT, Brady TJ, Rosen BR, Belliveau JW (1995). Functional analysis of human MT and related visual cortical areas using magnetic resonance imaging. *J Neurosci* 15:3215–3230.

- Umiltà MA, Kohler E, Gallese V, Fogassi L, Fadiga L, Keysers C, Rizzolatti G (2001). I know what you are doing: a neurophysiological study. *Neuron* 31:155–165.
- Ungerleider, L.G. & Desimone, R. (1986). Cortical projections of visual area MT in the macaque. *J. Comp. Neurol.*, 248, 190-222.
- Urgesi, C., Berlucchi, G. & Aglioti, S. M. (2004). Magnetic stimulation of extrastriate body area impairs visual processing of nonfacial body parts. *Curr. Biol.* 14, 2130–2134.
- Urgesi C, Moro V, Candidi M, Aglioti SM. (2006a). Mapping implied body actions in the human motor system. *J Neurosci.* 26(30):7942-9.
- Urgesi C, Candidi M, Fabbro F, Romani M, Aglioti SM. (2006b). Motor facilitation during action observation: topographic mapping of the target muscle and influence of the onlooker's posture. *Eur J Neurosci.* 23(9):2522-30.
- Urgesi, C., Candidi, M., Ionta, S. & Aglioti, S. M. (2007). Representation of body identity and body actions in extrastriate body area and ventral premotor cortex. *Nature Neurosci.* 10, 30–31.
- Verfaillie K. (2000). Perceiving human locomotion: priming effects in direction discrimination. *Brain Cogn.* 44(2):192-213.
- Verfaillie K. & Daems A., (2002). Representing and anticipating human actions in vision. *Vis Cogn* 9:217–232.
- v. Holst, E, Mittelstaedt, H (1950). Das Reafferenzprinzip. *Naturwissenschaften* 37 (20) 464-76. DOI 10.1007/BF00622503
- Wasserman EM (1998). Risk and safety of repetitive transcranial magnetic stimulation: report and suggested guidelines from the International Workshop on the Safety of Repetitive Transcranial Magnetic Stimulation, June 5–7, 1996. *Electroencephalogr Clin Neurophysiol* 108:1–16.
- Wilson, M., & Knoblich, G. (2005). The case of motor involvement in perceiving conspecifics. *Psychological Bulletin*, 131(3):460-473.
- Wohlschlager, A., & Bekkering, H. (2002). Is human imitation based on a mirror-neurone system? Some behavioural evidence. *Experimental Brain Research*, 143(3), 335_341.
- Yin, R. K. (1969). Looking at upside-down faces. *J. Exp. Psychol.* 81, 141–145.
- Young A.W., Ellis A.W., Flude B.M., (1988). Accessing stored information about familiar people. *Psychological Research*, 50, 111 – 115.
- Zeki S, Watson JD, Lueck CJ, Friston KJ, Kennard C, Frackowiak RS (1991). A direct demonstration of functional specialization in human visual cortex. *J Neurosci* 11:641–649.

12. Acknowledgements.

I would like to express my deepest gratitude to my supervisor Salvatore Maria Aglioti. His scientific knowledge, enthusiasm and human sensitivity have decisively stimulated my scientific interests, my personal development and helped me in my difficult moments.

I want to thank Cosimo Urgesi who taught me a lot as a researcher and person. Much of what I know and have done in these years is tied up with his determination.

I am grateful to Alessio Avenanti, Ilaria Minio Paluello, Ilaria Bufalari, Filippo Crostella, Silvio Ionta, Alissa Dora Fourkas, Viviana Betti, Anna Laura Sforza, Elia Valentini, Carmelo Mario Vicario, Enea Francesco Pavone, Ana Maria Abreu, Mariella Pazzaglia, Emiliano Pes, Valentina Palma and all the people from the lab for their important help in these years as colleagues and friends.

To my family that gave me faith and strength.

To Simona who shared with me all my difficulties and bears with me the burden of my fear.

13. APPENDIX: ORIGINAL PUBLICATIONS

Candidi M., Urgesi C., Ionta S., Aglioti S.M., (2008). Virtual Lesion of Ventral Premotor Cortex Impairs Visual Perception of Biomechanically Possible but not Impossible Actions. *Social Neuroscience* First published on 16 October 2007. DOI: 10.1080/17470910701676269.

Urgesi, C., **Candidi, M.**, Ionta, S. & Aglioti, S. M. (2007). Representation of body identity and body actions in extrastriate body area and ventral premotor cortex. *Nature Neurosci.* 10, 30–31.

Urgesi C, Moro V, **Candidi M**, Aglioti SM. (2006). Mapping implied body actions in the human motor system. *J Neurosci.* 26(30):7942-9.

Urgesi C, **Candidi M**, Fabbro F, Romani M, Aglioti SM. (2006). Motor facilitation during action observation: topographic mapping of the target muscle and influence of the onlooker's posture. *Eur J Neurosci.* 23(9):2522-30.