

Object Presence Modulates Activity within the Somatosensory Component of the Action Observation Network

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In the present study, we used functional magnetic resonance imaging to investigate the influence that the presence of an object, intended as the target for an action, might have on the neural circuit underlying the observation of the movement of others (action observation network [AON]). This system entails a simulation process of the observed movement occurring via the recruitment of the motor and somatosensory cortices involved in the execution of such movement. Here, participants were requested to observe grasping actions ending behind a partition knowing in advance whether a target-object would be present (i.e., object-directed action) or absent (i.e., non object-directed action). These “action” conditions were compared with “control” conditions in which a stationary hand was presented either alone or together with the target-object hidden behind the partition. Activation within most regions of the AON was similar for observing partially occluded object-related and non object-related actions. However, within one of the regions belonging to the AON, namely in the somatosensory cortices, blood oxygen level-dependent activity was modulated by the presence of a target-object. We interpreted such modulation as demonstration of the differential involvement of the somatosensory component of the AON for the coding of these 2 types of actions.

Keywords: action observation, fmri, grasping, mirror neurons, motor system

Introduction

The study of how human beings perceive actions had a huge proliferation following the discovery of mirror neurons in the monkey premotor (area F5c) and, subsequently, within parietal (area PF/PFG) cortices (di Pellegrino et al. 1992; Gallese et al. 1996; Rizzolatti, Fadiga, Fogassi, et al. 1996; Umiltà et al. 2001; Fogassi et al. 2005; Rozzi et al. 2008; Caggiano et al. 2009). These neurons discharge not only when a monkey performs a specific motor act, intended as an object-directed movement (e.g., grasping an object), but also when it observes the execution of a similar motor act.

The discovery of neurons within the motor system possessing a visuomotor response was the first demonstration of the possible involvement of such a system in a cognitive domain—that is, the recognition and understanding of actions. The fundamental characteristic of these neurons supporting such a notion was their extremely selective response during action observation. Central to the original description of these neurons was the presence of a goal-object as a necessary condition in order to trigger a discharge within the recorded neuron (e.g., Gallese et al. 1996; Rizzolatti, Fadiga, Fogassi, et al.

1996; Rizzolatti, Fadiga, Matelli, et al. 1996; Umiltà et al. 2001). Observing pantomimed versions of the same motor acts or simple movements, such as flexion or extension of the fingers, was not sufficient to elicit a neuronal response (for a thorough discussion on the distinction between movements and motor acts see Rizzolatti and Sinigaglia [2010]).

These neurophysiological findings have prompted an explosion of investigations aimed at uncovering the existence of similar regions within the human brain using neuroimaging techniques (Grafton et al. 1996; Rizzolatti, Fadiga, Matelli, et al. 1996; Decety et al. 1997; Grèzes et al. 1999; Buccino et al. 2001, 2004; Cross et al. 2006, 2009; Gazzola et al. 2007; Gazzola and Keysers 2009; Turella et al. 2009; Ramsey and Hamilton 2010; Tubaldi et al. 2010). The consistent result is the revelation of a widespread network of brain regions that is automatically activated when perceiving other people's actions. This system, termed as the “action observation network” (AON), includes frontal, parietal, and temporal regions (Buccino et al. 2001; Gazzola et al. 2007; Gazzola and Keysers 2009; Turella et al. 2009). In detail, consistent activation was reported in the following cerebral regions: for the frontal cortex, within the dorsal and ventral premotor cortex together with the inferior frontal gyrus; for the parietal cortex, within both the superior and inferior parietal lobules, the intraparietal cortex and within the postcentral gyrus; for the temporal cortex, within the superior and middle temporal gyri (Buccino et al. 2001; Brass and Heyes 2005; Gazzola et al. 2007; Gazzola and Keysers 2009; Turella et al. 2009; for a meta-analysis, see Caspers et al. 2010).

Recent neuroimaging monkey studies, using the [¹⁴C]-deoxyglucose autoradiographic method, provided further support to the notion that the neural correlates elicited by the observation of grasping actions were not limited to mirror regions F5c and PF/PFG but comprised a network of frontal, parietal, and temporal cerebral regions (Raos, Evangeliou, et al. 2004; Raos et al. 2007; Evangeliou et al. 2009). These findings were the first demonstration that even in monkeys a widespread AON is present and that similar regions are automatically recruited in both species.

Altogether such evidence indicates that the AON allows for the recognition and the understanding of observed actions via a mechanism of motor and somatosensory simulation (Blakemore and Decety 2001; Goldman and Sebanz 2005; Raos et al. 2007; Gazzola and Keysers 2009; Grafton 2009). In detail, simulation of the motor properties concerned with the observed action seems to be located within a frontal node, comprising the premotor cortex and the inferior frontal gyrus, and a parietal node, comprising the anterior part of inferior

parietal lobule and the anterior part of the intraparietal cortex. “Somatosensory” simulation seems to be obtained through the recruitment of the somatosensory cortices (Raos, Evangeliou, et al. 2004; Raos et al. 2007; Evangeliou et al. 2009; Keyzers et al. 2010). Part of the primary somatosensory cortex (in particular Brodmann area 2, see Keyzers et al. 2010) appears to be mainly recruited during the observation of actions, whereas the secondary somatosensory cortex (SII) appears to be chiefly activated during the observation of touch (Keyzers et al. 2004; see Keyzers et al. 2010).

Although the AON in its entirety seems to be recruited during the proposed simulation processes, specific regions appear to be responsible for the coding of the different properties characterizing the observed actions. Here, we focus on a peculiar feature of the human AON system which has been reported in a variety of neuroimaging studies: its recruitment during the observation of non object-related rather than object-related actions (Decety et al. 1997; Grèzes et al. 1999; see also Rizzolatti and Fabbri-Destro 2008).

In this respect, pioneering research demonstrated that various aspects of the observed non object-directed actions such as their content (meaningful vs. meaningless) and their degree of novelty (learned vs. unknown stimuli) can modulate activation within the human AON (Decety et al. 1997; Grèzes et al. 1999). More recently, such notion has been extended to the coding of actions performed by animated characters (Pelphrey et al. 2004, 2005), by effectors other than the hand such as the mouth or the leg (Buccino et al. 2001; Wheaton et al. 2004), by actions which are part of the rock-paper-scissors game (Dinstein et al. 2007, 2008, 2010), and by the pantomime of complex actions (Chong et al. 2008). Finally, not only observation but also imagery of different types of non object-directed actions activated similar cerebral regions within the AON (Lui et al. 2008).

This series of neuroimaging studies points to a recruitment of the human AON for the coding of non object-related actions. Therefore, in contrast to the original description of the monkey AON, the human AON seems to be involved in the coding of actions that are not directed toward an object. This means that the presence of a goal-object is not a fundamental and necessary condition for its recruitment. As a consequence, if the AON is responsible for understanding both types of actions, then it should be able to discriminate between them.

In this connection, only few of the above mentioned studies had the potential to unveil whether the human AON can effectively discriminate between object-related and non object-related actions (Buccino et al. 2001; Grèzes et al. 2003; Pelphrey et al. 2004). For instance, Buccino et al. (2001) found a bilateral involvement of the parietal cortices only for the coding of object-directed actions. This result might be suggestive of a differential coding for the 2 types of action within these regions. But, in this study, object-directed and non object-directed actions were not directly contrasted. Therefore, the possibility that the AON, or a part of it, might be able to discriminate between these kinds of actions can only be drawn on the basis of indirect evidence.

Finding an appropriate manner as to test for a differential coding within the AON for fully visible object and non object-related actions is not an easy task. An interpretational issue arises when directly contrasting the pattern of activity classically elicited by these 2 types of action. That is, part of the differential activation might be ascribed to the presence of

the object per se rather than to the representation of the action goal. Support of this contention comes from neurophysiological and neuroimaging studies. In monkeys, neurons responding to the simple observation of graspable objects (i.e., “canonical” neurons; Murata et al. 1997, 2000; Raos, Umiltà, et al. 2004; Raos et al. 2006; Rozzi et al. 2008) have been found within the very same or near cortical regions in which cells responding to action observation were detected. In humans, neuroimaging evidence points to a similar direction demonstrating the automatic recruitment of premotor and parietal cortices during the observation of static graspable objects or tools (Grafton et al. 1997; Chao and Martin 2000; Grèzes and Decety 2002; see also Króliczak et al. 2008, adopting a functional magnetic resonance imaging fMRI-adaptation protocol) and the coding of the goal of an observed action (Hamilton and Grafton 2006, 2007, 2008; Grafton 2009).

At this stage, the question is: how can we explore the modulation determined by the presence/absence of a goal-object within the human AON avoiding such an interpretational confound? An elegant neurophysiological paradigm might provide the ideal opportunity for such testing (Umiltà et al. 2001). Specifically, this study revealed that some F5c mirror neurons responded even when the final part of an observed grasping action was hidden behind a partition. The prerequisite for this to happen was that the monkey knew there was an object behind the partition (Umiltà et al. 2001). The same neurons did not discharge when the monkey observed a pantomime of the same action both in full vision or hidden by the same partition—that is, when the animal knew that there was no object behind the partition. These findings, therefore, seemed to indicate that previous knowledge regarding the presence of a goal-object might suffice to distinguish between object and non object-directed actions.

Here, we capitalized on this paradigm to uncover a possible modulation within the human AON, in particular within parietal and premotor cortices, depending on the goal of the observed action without the possible confound of object-related activation. Participants were requested to observe video-clips showing a model performing a grasping action toward an object that was hidden behind a partition or the very same action in the very same contextual conditions but in the absence of the goal-object (i.e., pantomimed grasp). A “prime” video-clip presented before the stimulus representing either the real or the pantomimed grasp conveyed the information regarding the presence or absence of the goal-object behind the partition. This procedure might permit a specific investigation of whether the presence/absence of the object, intended as the goal of the action, modulated activity within the AON during the observation of partially hidden actions. In addition, the presence of the partition allowed for the introduction of 2 controls that are fundamental to the interpretation of the results. First, by inserting the partition, we avoided a direct comparison between fully visible object-related actions and pantomimed grasps. The pattern of activity stemming from such contrast could have been ascribed to the mere presence of the object (canonical activation) rather than to the properties of the action goal. Second, the introduction of the partition allowed us to use the same video-clips for the “grasping” and the “pantomime” conditions, thus minimizing potential confounds due to subtle differences in kinematics.

To sum up, if the same visual stimulus can modulate activity within the AON on the basis of previous knowledge regarding

the presence of an unseen goal-object, then it might be argued that the system is able to discriminate between object and non object-related actions. In turn, this will allow inferences regarding how the representation of a goal is coded within the AON by eliminating the subtle confounds related to “how” an action is performed.

Materials and Methods

Subjects

Nineteen right-handed paid volunteers (9 males, mean age 27.2 years, range 20–37) were recruited for the present study. They all had normal or corrected-to-normal vision and had no history of neurological problems. Informed consent was obtained from all participants before the testing session in accordance with the declaration of Helsinki.

Stimuli

Video-clips (AVI format, Xvid codec compression, resolution 320 × 240, 25 frames per second) were used as stimuli for the 2 parts characterizing the present study, namely the “AON Localizer” and the “Main Experiment.” The stimuli used for the AON Localizer represented: 1) the hand of a model grasping and lifting an object resting on a table (see Fig. 1Aa) and 2) the hand of a model resting near an object (see Fig. 1Ab). For the implementation of these video-clips, 2 different individuals (one right-handed and one left-handed) served as models and 4 objects were used as target stimuli for the models’ action (i.e., a sphere of 3.5-cm diameter; a sphere of 9-cm diameter; 2 parallelepipeds measuring 9 × 6 × 6 and 6 × 2.5 × 2.5 cm, respectively). Furthermore, object position was counterbalanced with respect to the participants’ point of view. For half of the video-clips, the object was located to the left, whereas for the other half, the object was located to the right side of the screen upon which the stimuli were presented. The combination of the considered factors (2 models × 4 objects × 2 positions) resulted in a total of 16 videos.

The Main Experiment considered 3 specific events: 1) prime (duration: 1 s); 2) experimental condition (duration: 3 s); and 3) question (duration: 2 s). For the prime event, the stimuli represented an object resting on a table, which was fully visible at the beginning of the video and then gradually covered by means of a gray partition (see Fig. 1Ac) and the same visual scene in the absence of the object (see Fig. 1Ad). For this event, the stimuli were constructed starting from static frames depicting an object resting on a table or the same scene without the object. The moving gray partition was added using a video-editing technique. This partition entered the scene at the beginning of the video-clip and its motion ended when the object was fully hidden. When the object was absent, the partition ended at the same position as when the object was present. A total of 10 videos were adopted (8 video-clips with the object and 2 video-clips without the object). For the “experimental condition” event, the stimuli represented the hand of a model grasping an object hidden behind the partition (see Fig. 1Ae) and the hand of a model maintained static near the partition (see Fig. 1Af). For this event, the stimuli were in all cases edited versions of the video-clips used for the AON Localizer. Here, a static gray partition was present for the entire duration of the video-clip. The stimulus for the “question” event corresponded to a string of text appearing on the screen. Video-clips were edited using the software Adobe Premiere (www.adobe.com) and presented using the software Presentation (www.neuro-bs.com), which ensured synchronization with the MR scanner. A projector was employed to display the stimuli on a screen (20 × 15° of visual angle). The stimuli were made visually available to participants via a mirror mounted on the head coil.

Tasks, Procedures, and Experimental Design

AON Localizer

The AON Localizer was performed as to identify the network of regions automatically activated by the observed actions (i.e.,

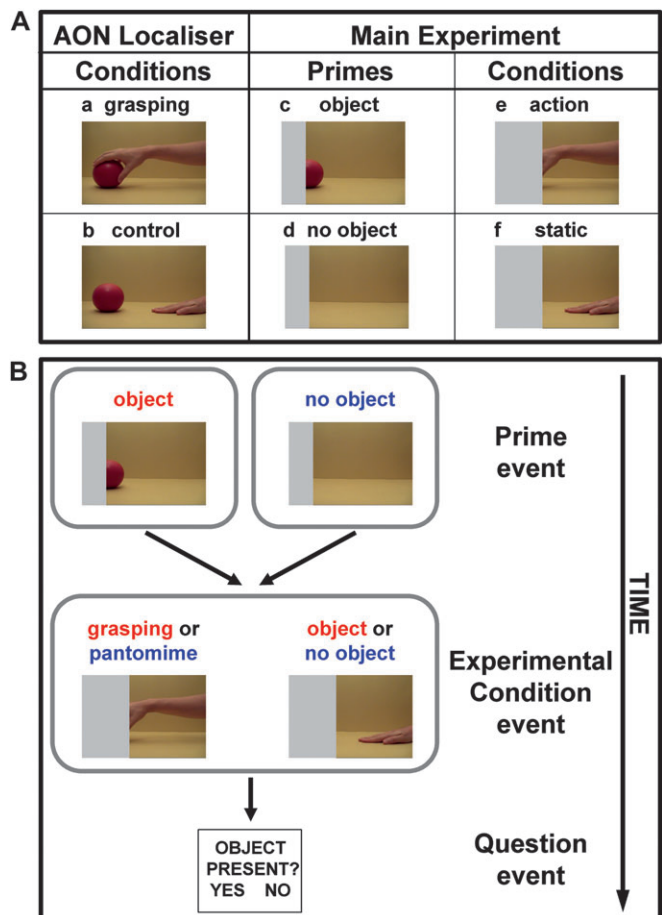


Figure 1. (A) Types of stimuli. For the AON localizer, 2 types of video-clips were adopted (grasping and control). The represented frames (Fig. 1Aa,b) were extracted from the central part of the video-clips. For the main experiment, 4 types of videos were adopted: Two for the prime event (object and no object) and 2 for the experimental condition event (action and static). The represented frames for both prime conditions (Fig. 1Ac,d) and for the experimental conditions (Fig. 1Ae,f) are extracted from the central part of the video-clips. (B) Timeline of an experimental trial. Graphic representation for the sequence of events. The represented frames for the prime conditions were extracted from the central part of the video-clips. For the primes, the partition was still not covering the entire part of the scene as in the experimental conditions.

the AON). For this reason, we requested the participants to attend the stimuli without performing any additional task (for a similar procedure, see Buccino et al. 2001; Gazzola et al. 2007; Gazzola and Keysers 2009). The localizer consisted of a single run during which participants were requested to carefully observe the stimuli described above. This part of the experiment was always administered following the Main Experiment, for 2 main reasons. First, because there might be the possibility that if performed before the Main Experiment it might have biased the subject toward perceiving the actions as object-related. Second, the subjects might have thought that the video-clips presented within the localizer were the same as those presented for the Main Experiment.

There were 2 experimental conditions: 1) an “object-related grasping” condition in which participants observed a model performing a grasping action and 2) a “static” control condition, in which participants observed the hand of a model resting on a table near an object. The 2 experimental conditions were presented in an alternated block design.

Within each block, 4 video-clips were displayed for 3 s and were separated by 0.5-s intervals of blank screen (total block duration: 13.5 s). Consecutive blocks were separated by a 12.5-s rest period during which a gray screen with a black fixation cross was presented. Each condition was repeated 16 times.

Main Experiment

The procedures for the Main Experiment largely relied on those previously used in a neurophysiological study by Umiltà et al. (2001). Naturally, they were modified in order to fit the needs for an fMRI study. The sequence of events was as follows (for the specific trial timeline, please refer to Fig. 1*B*). The first event was a prime. There were 2 types of prime: an “object” prime, in which the stimulus represented an object resting on a table (Fig. 1*B*; red labeling) and a “no object” prime, in which the object was absent (Fig. 1*B*; blue labeling). Following this, a gray partition entered the scene and covered either the part of the scene in which the object was present (object prime in Fig. 1*B*) or the corresponding empty area (no object prime; Fig. 1*B*). The second event experimental condition varied depending on the type of prime. When the prime signaled the presence of an object located behind the partition (Fig. 1*B*; left upper panel) the stimuli for this event could be either 1) the hand of a model grasping the object (grasping option within the left bottom panel in Fig. 1*B*) or 2) the model’s hand maintained static (object option within the right bottom panel in Fig. 1*B*). When the prime signaled the absence of an object behind the partition (Fig. 1*B*; right upper panel) the stimuli for the experimental condition event were either 1) the hand of a model performing a pantomimed grasp (pantomime option within the left bottom panel in Fig. 1*B*) or 2) the model’s hand maintained static (no object option within the right bottom panel in Fig. 1*B*). For the third event termed ‘question’ (Fig. 1*B*), a text line appeared on the screen for 2 s and participants were requested to indicate whether during the 2 previous events the object was absent or present. They pressed the left key of an MRI-compatible response box with the index finger of the right hand if the object was present or the right key with the middle finger if the object was absent. Trials were considered successful only when the response was congruent with the prime. When the response was incorrect, the trial was considered an error and, subsequently, discarded. The mean percentage of errors across participants was about 3.3% (6.3 trials over a total of 192). In order to ensure that participants fully understood the task, they attended a practice session outside the scanner. They were also requested to pay attention to all the events within the study. Regarding the task, here participants had to simply focus their attention on the presence/absence of the object. This applies to all the experimental conditions. If different tasks had been adopted, then the contrasting of different events would not have resulted in an activation that could only be ascribed to a stimulus-specific effect. Furthermore, this type of task does not directly imply the interpretation of the intentions behind the model’s action—a process which may recruit activity within regions of the so-called “mentalizing” network (Frith CD and Frith U 2006; de Lange et al. 2008; Van Overwalle 2008; Van Overwalle and Baetens 2009).

The considered experimental conditions were embedded in a 2 × 2 factorial design, with 2 within-subjects factors: “observed task” (action vs. control) and object (presence vs.

absence). The combination of the 2 factors brought to 4 conditions of interest:

1. grasping condition, in which participants observed the model grasping an object hidden behind a partition. Participants knew from the type of prime that an object was present.
2. pantomime condition, in which participants observed the model performing a grasping action knowing from the type of prime that there was no object behind the partition.
3. object condition, in which participants observed a static hand and a partition knowing from the type of prime that behind the partition there was an object.
4. no object condition, in which participants observed a static hand and a partition knowing from the type of prime that there was no object behind the partition.

As reported above within the Stimuli section, only 2 sets of videos were used as stimuli for the experimental conditions: one set was used for the “action” conditions (i.e., grasping and pantomime) and one set for the “control” conditions (i.e., object and no object). Within each of the 3 functional runs, 64 video-clips were presented semirandomly (16 for each experimental condition). The total duration for each trial was 14 s (7 time repetitions [TR]). The time line for each trial was the following: the prime event was presented only within the first 2 TRs, the experimental condition event was presented only from the third to the fifth TRs, and the question event within the last 2 TRs (i.e., sixth and seventh). All the stimuli started on a variable schedule, determining a jittered interstimulus interval between the 3 events of each trial (prime, experimental condition, and question).

Data Acquisition

Whole-brain data were acquired on a 3-T Magnetom Trio Scanner (Siemens, Erlangen, Germany) equipped with a 12-channel head array RF coil. Functional images were obtained with the signal of echo planar images (EPI) T_2^* -weighted sequence in order to measure blood oxygen level-dependent (BOLD) contrast throughout the whole brain (TR = 2000 ms, echo time [TE] = 33 ms, field of view 192 × 192 mm, matrix 64 × 64, in-plane resolution 3 × 3 mm, slice thickness = 3.5 mm, 0.7-mm gap, 32 slices). Scans were acquired for each participant in different scanning runs, 3 runs (462 volumes each) for the observation part of the experiment and one for the localizer (425 volumes). The first 5 volumes of every run were discarded due to initial instability in the signal of EPI images. High-resolution T_1 -weighted images were also acquired for each participant during the experimental session (magnetization prepared rapid gradient echo, TR = 2300 ms, TE = 3.03 ms, flip angle = 8°, field of view 224 × 256 mm, 1-mm isotropic voxels, 160 slices).

Data Preprocessing

fMRI data were analyzed using Statistical Parametric Mapping software (SPM5, www.fil.ion.ucl.ac.uk/spm), implemented in Matlab (version 7.9, www.mathworks.com). All the functional images collected for the AON Localizer and the Main Experiment were realigned using a 2-step procedure: registering to the first functional volume of each series and then to the mean image in order to correct for any head movement occurring during the entire investigation. Then, high-quality T_1

images were skull stripped using BET (Smith 2002), part of FSL software (www.fmrib.ox.ac.uk/fsl). Skull-stripped T_1 images were coregistered to the mean EPI image and segmented using SPM5. The coregistered gray matter segment was normalized onto the gray matter template and the resulting normalization parameters applied to all functional images (resampling the voxels at $2 \times 2 \times 2$ mm). Finally, data were spatially smoothed using 6-mm full-width at half-maximum Gaussian kernel.

Data Analysis

AON Localizer

For the AON localizer, whole-brain analysis was performed by applying the general linear model (GLM) for analysis of fMRI time series implemented in SPM5 (Friston et al. 1995). A high-pass temporal filter (cutoff 128 s) was applied to the time series. Regressors were defined based on the timing of presentation for each of the conditions and were modeled using a boxcar function convolved with the hemodynamic response function (HRF). In addition, predictors of no interest were modeled to account for residual effects of the movements measured during the realignment procedure. The images referring to the contrast between object-related grasping observation and static control were extracted for each subject at first level and then tested in a second-level random effect analysis using a one-sample t -test. The adopted statistical threshold was set at $P < 0.01$ false discovery rate (FDR) corrected at voxel level (Genovese et al. 2002) and at least 10 contiguous voxels.

This contrast strictly defined regions within the AON, that is, automatically activated during the observation of actions even if the subject was not performing any task on the stimuli apart from attending them carefully.

Main Experiment

As our specific interest was to test the modulation within the AON, we used an inclusive masking approach limiting the analysis of the main experiment within the regions found activated in the AON localizer. Using different data for the 2 parts of the study allowed us to avoid circularity, adopting an independent selection criterion (i.e., AON Localizer) for our subsequent selective analysis (i.e., Main Experiment, see Friston et al. 2006; Friston and Henson 2006; Kriegeskorte et al. 2009). This analysis for the main experiment was carried out by applying the GLM for analysis of fMRI time series implemented in SPM5 (Friston et al. 1995). Regressors were defined based on the onset times for the experimental conditions, primes, responses, and errors. All regressors were defined using a delta function convolved with a canonical HRF. Primes, responses, errors together with predictors related to residual movement effects were defined as regressors of no interest.

The main experiment entailed a 2×2 factorial design, so we tested the main effect of observed task, "object presence" and the 2 interactions. As it might be that the effects within the AON might be subtle, we adopted a less conservative but still corrected threshold for these comparisons (P -values set at $P < 0.05$ FDR corrected at voxel level and at least 10 contiguous voxels). To test for the type of modulation occurring within the cerebral areas activated for the interaction contrasts, the mean percent signal change (PSC), extracted by using *rfxplot* Toolbox (Gläscher 2009) based on Marsbars Toolbox (Brett

et al. 2002), was analyzed by means of a repeated measures analysis of variance (ANOVA). Then we performed paired t -tests in order to understand the type of modulation determined by the presence/absence of the object. To adopt a correction for multiple comparisons, we set the critical P value at 0.0125 uncorrected (equivalent to a basic threshold of $P = 0.05$ divided by 4, the number of performed comparisons).

For a complete overview of the regions involved in our task, in particular regarding the mentalizing system, we have also conducted a whole-brain analysis without adopting the masking procedure (see Supplementary materials).

Localization of the Results

In order to obtain a high specificity in terms of anatomical localization of our results, we adopted 2 complementary methodologies. First, we used 2 atlases as a general neuroanatomical reference (Duvernoi and Bourgouin 1999; Mai et al. 2004). Second, the SPM Anatomy Toolbox (Eickhoff et al. 2005, 2007) based on 3D probabilistic cytoarchitectonic maps was used to determine the cytoarchitectonic probability, when available, of the peak activity of voxels and of the regions comprised within each cluster.

Results

AON Localizer

When contrasting the 2 conditions characterizing the AON localizer (object-related grasping observation > static control) activation was evident bilaterally within parietal, temporal, and occipital cortices with a left lateralization of activity within the premotor cortex (see Table 1 and Fig. 2A). In general, this is in line with previous literature demonstrating an automatic involvement of these areas during a passive action observation task (Buccino et al. 2001; Gazzola et al. 2007; Gazzola and Keysers 2009; Turella et al. 2009, Caspers et al. 2010). More specifically, bilateral activation was present within the inferior, the middle, and the superior occipital cortex. For the temporal lobes, activity was detected bilaterally within the inferior and the middle temporal cortex. Within the superior temporal gyrus, a cluster was activated only within the right hemisphere. Bilateral activated parietal regions covered the superior parietal lobules, spreading within regions of the intraparietal sulcus and within the postcentral gyrus. The left lateralised parietal cluster activity also covered the inferior parietal lobule chiefly within the supramarginal gyrus. Frontal lobe activation was evident in 2 clusters, one within the left dorsal and one within the left ventral premotor cortex, the latter cluster of activation spreading also within the pars opercularis of the inferior frontal gyrus. Activation was also present within the cerebellum and the left thalamus.

Main Experiment

The main effect of observed task was tested with the following t -contrast (grasping + pantomime > object + no object). Significant activation was evident in all the regions found to be activated within the AON localizer (see Table 2 and Supplementary Fig. S1). No significant activity was evident for the main effect of object presence (grasping + object > pantomime + no object). Similarly, no significant activation was found when setting P values at the $P < 0.001$ uncorrected threshold.

Table 1

Regions found activated for the AON Localizer

Peak anatomical localization	Peak probabilistic cytoarchitecture ^a	Regions within the cluster ^b	x	y	z ^c	t value
Frontal cortex						
Left precentral gyrus	BA 6: 20%	BA 6	-26	-12	52	5.7
Left precentral gyrus	BA 44: 40%	BA 6, BA 44	-54	6	24	4.93
Parietal cortex						
Left superior parietal lobule	SPL (7PC): 70%	IP (hIP3), IPC (PF, PFt, PFop), SI (BA2), SPL (7A, 7PC)	-34	-48	58	7.58
Right superior parietal lobule	SPL (7PC): 70%	SI (BA 2), SPL (5L, 7PC)	28	-52	62	4.96
Right postcentral gyrus	BA 2: 100%	SI (BA2, BA 3a, BA3b), SPL (7PC)	42	-38	54	6.14
Temporal cortex						
Right middle temporal gyrus	NA	ITG, MTG (hOC5), SOG, MOG	48	-58	4	10.06
Right superior temporal gyrus	IPC (PFm): 40%	IPC (PF, PFm, PFcm)	56	-42	16	5.21
Occipital cortex						
Left calcarine gyrus	BA 18: 30%	CG (BA 17, BA 18)	-4	-90	-12	8.94
Left middle occipital gyrus	NA	ITG, MTG, MOG (hOC5)	-50	-72	4	13.15
Left middle occipital gyrus	BA 18: 40%	MOG (BA 18)	-22	-94	14	5.97
Left superior occipital gyrus	BA 18: 10%	SOG	-22	-88	24	4.77
Right superior occipital gyrus	NA	SOG	26	-80	36	5.43
Cerebellum						
Left lobule VI	hOC4v (V4): 20%	Lobule VI	-20	-74	-16	5.23
Right lobule VI	Lobule VI: 95%	Lobule VI, lobule VIIa	18	-70	-22	7.47
Right lobule VIII	Lobule VIIa: 49%	Lobule VIIb, lobule VIIa, lobule VIIa	10	-72	-42	6.78
Right lobule VI	Lobule VI: 84%	Lobule VI, lobule VIIa	34	-44	-36	6.14
Subcortical structures						
Left thalamus	NA	Left thalamus	-16	-32	0	5.76

^aMost probable localization of the activation peak based on the probabilistic cytoarchitecture provided by Anatomy Toolbox v 1.7 (Eickhoff et al. 2005, 2007). Conventions are the same adopted in the Toolbox, apart from NA, which stands for "not assigned."

^bCerebral regions comprised within the cluster. When available, we reported the cytoarchitectonic probabilistic assignment of each cerebral region that accounted for at least 5% of the extent of the cluster (see Eickhoff et al. 2005, 2007). If not available, we reported the anatomical region. Abbreviations: CG, calcarine gyrus; IPC, inferior parietal cortex; IP, intraparietal cortex; ITG, inferior temporal gyrus; MOG, middle occipital gyrus; MTG, middle temporal gyrus; SI, primary somatosensory cortex; SOG, superior occipital gyrus; SPL, superior parietal cortex. Other conventions are the same adopted in the Toolbox, apart from NA, which stands for not assigned.

^cStereotaxic coordinates in MNI space are reported in mm.

The analysis for the 2 interactions showed significant bilateral activity within the somatosensory cortices for the positive interaction (grasping – pantomime > object – no object, see Table 3 and Fig. 2B) and no significant activation for the negative interaction (pantomime – grasping > no object – object). Even for this contrast, no significant activation was found at the $P < 0.001$ uncorrected threshold.

Analysis of the Regions Found Activated within the Interaction

Analysis was performed on the PSC extracted from the cerebral regions activated at the level of the interaction, that is, 2 clusters were bilaterally activated, one within the left and the other within the right somatosensory cortex (see Table 3 and Fig. 2B). Both clusters were located within the postcentral gyrus and based on probabilistic cytoarchitectonic maps mainly within Brodmann area 2 (98.1% of the left cluster and 52.1% of the right cluster, Grefkes et al. 2001). Within both regions, the main effect of observed task ($F_{1,18} = 27.684$, $P < 0.001$ and $F_{1,18} = 42.908$, $P < 0.001$, for right BA 2 and left BA 2, respectively) and the interaction were significant ($F_{1,18} = 16.229$, $P < 0.001$ and $F_{1,18} = 13.741$, $P = 0.002$, for right BA 2 and left BA 2, respectively). Main effects of object were not significant ($F_{1,18} = 2.011$, $P = 0.173$ and $F_{1,18} = 3.318$, $P = 0.085$, for right BA 2 and left BA 2, respectively). For the main effect, pairwise comparisons demonstrated a significant difference contrasting each action condition, grasping and pantomime, against its own control condition, object and no object, respectively (see Table 4 and Fig. 2B). To explore the interaction, we performed paired t -tests contrasting grasping versus pantomime conditions and object versus no object conditions. The results demonstrated that activity was higher when participants were exposed to the grasping rather than to the pantomime

condition (see Table 4 and Fig. 2B). No difference in activity was found for the considered areas when comparing object versus no object conditions (see Table 4 and Fig. 2B). Thus, the results demonstrated that these regions were activated for both object-related and nonobject-related actions. But, they showed a selective modulation due to the presence/absence of an object only when an action was observed.

ROI Analysis of the Response within Ventral Premotor Cortex

As it might be that our voxelwise approach was not sensitive enough to unveil subtle effects within all the regions of the AON, we decided to perform a ROI analysis within one region of such system, that is, left ventral premotor cortex (see Table 1 for coordinates of the peak and Fig. 2C for anatomical localization). This region could be expected to show a differential effect in BOLD response based on the previous monkey neurophysiological study that prompted our investigation (Umiltà et al. 2001). ROI analysis was performed on the PSC extracted from the voxels of the ventral premotor cortex activated within the AON localizer. A repeated measures ANOVA testing for the main effects and the interaction was performed on PSC. The main effect of action observation was significant ($F_{1,18} = 21.268$, $P < 0.001$), but neither the main effect of object ($F_{1,18} = 0.858$, $P = 0.366$) nor the interaction ($F_{1,18} = 0.943$, $P = 0.344$) were significant (see Fig. 2C).

Discussion

We set out to investigate whether activity within the AON was differentially modulated by the observation of object-related and nonobject-related actions. To this end, participants were requested to observe a model performing a grasping action toward an object that was hidden behind a partition, or the

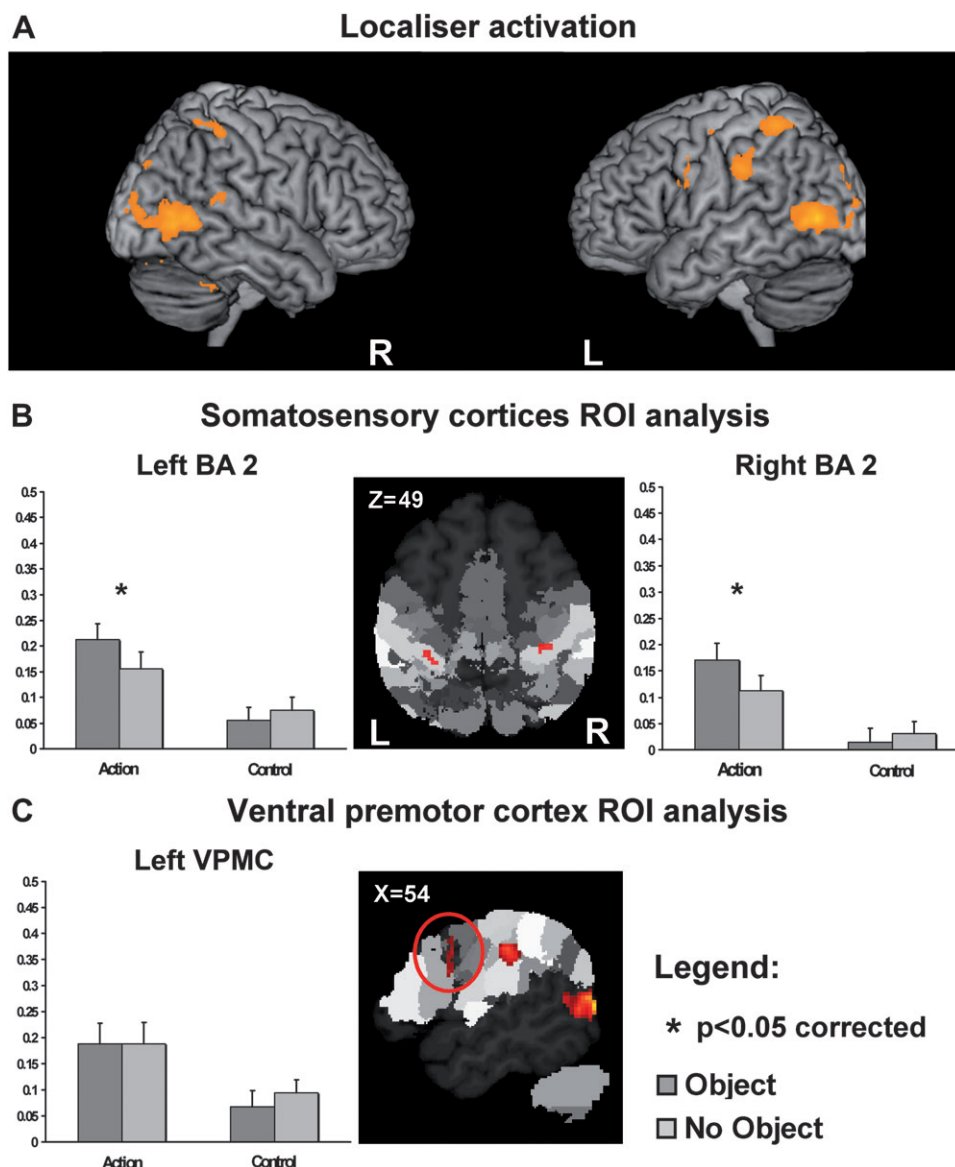


Figure 2. (A) Activation maps for the AON localizer. Activation for the AON localizer is rendered on the template provided within Mricron (<http://www.cabiatl.com/micron/micron/index.html>). The threshold was set as in the original analysis. (B) ROI results for somatosensory cortices. Plots of the PSC extracted from the regions of interest. Paired t -tests were performed on the conditions of interest. An asterisk defines significance given a critical P value of $P < 0.05$ corrected (for uncorrected P values see Table 4). The exact t and P value of the contrasts are reported in Table 4. Clusters found activated within the interaction are superimposed on an axial slice together with the cytoarchitectonic maps of the Anatomy Toolbox version 1.7 (Eickhoff et al. 2005, 2007). The light gray areas surrounding and comprising the 2 clusters are BA 2. Error bars indicate standard error of the mean (SEM). (C) ROI results for left ventral premotor. Plot of the PSC extracted from the region. The cluster activated within the left ventral premotor cortex is indicated by a red circle. It comprised both BA 6 (dark gray) and BA 44 (light gray). Error bars indicate SEM.

very same action in the very same contextual conditions but in the absence of the goal-object. We found that both object-related and non object-related actions determined a similar level of activity within key regions of the AON. However, the somatosensory part of the AON (BA 2) was modulated by presence of a goal-object. As outlined below, these findings might have noteworthy implications for our understanding of how the AON selectively responds to the features characterizing observed actions.

Object and Non Object-Related Action Coding within the AON

The first aspect emerging from our study was that the human AON coded for both object-related and non object-related

actions. As already reported in a variety of fMRI studies (Grèzes et al. 2003; Oouchida et al. 2004; Pelphrey et al. 2004; Wheaton et al. 2004; Dinstein et al. 2007, 2008, 2010; Gazzola et al. 2007; Montgomery et al. 2007; Lui et al. 2008; Gazzola and Keysers 2009; Schippers et al. 2009; Tubaldi et al. 2010), the parietal part of the AON was recruited during the understanding of both types of action. With respect to non object-related actions, a pattern of activation similar to ours was found in a recent study by Lui et al. (2008), who demonstrated a modulation for different types of non object-related actions within the AON. Of interest, they found that the observation of mimed actions (i.e., pantomime of object-related actions) elicited activation within the parietal cortex similar to the pattern classically found when considering object-related actions (Buccino et al.

Table 2

Regions found activated for the main effect of observed task

Peak anatomical localization	Peak probabilistic cytoarchitecture ^a	Regions within the cluster ^b	x	y	z ^c	t value
Frontal cortex						
Left precentral gyrus	BA 6: 30%	BA 6, BA 44	-54	4	40	3.96
Left precentral gyrus	BA 6: 30%	BA 6	-26	-14	52	3.77
Parietal cortex						
Left supramarginal gyrus	IPC (PFt): 50%	IPC (PF, PFt, PFop), SI (BA 2)	-50	-26	32	4.89
Left superior parietal lobule	SPL (7PC): 50%	IP (hIP3), SI(BA 2), SPL (7A, 7PC)	-34	44	58	6.64
Right superior parietal lobule	BA 2: 30%	SI (BA 2), SPL (7PC, 5L)	28	-50	62	4.15
Right postcentral gyrus	BA 2: 50%	SI (BA 2, BA 3a, BA 3b), SPL (7PC)	32	-36	50	5.04
Temporal cortex						
Right middle temporal gyrus	NA	ITG, MTG (hOC5)	48	-68	8	12.75
Right superior temporal gyrus	IPC (PFm): 40%	IPC (PF, PFm, PFcm)	56	-42	16	8.47
Occipital cortex						
Left calcarine gyrus	Area 18: 80%	CG (BA 17, 18)	-2	-88	8	5.42
Left middle occipital gyrus	NA	BA 18	-24	-90	12	4.16
Left middle occipital gyrus	NA	ITG, MOG, MTG	-50	-72	4	13.86
Left superior occipital gyrus	NA	SOG	-22	-86	36	4.25
Right superior occipital gyrus	NA	SOG	24	-76	36	5.28
Cerebellum						
Left lobule VII	Lobule VIIb: 69%	Lobule VIIa, lobule VIIb, lobule VIIla	12	-76	-44	5.15
Left lobule VI	hOC4v (V4): 40%	Lobule VI	-20	-74	-14	4.31
Right lobule VI	Lobule VI: 75%	Lobule VI, lobule VIIa	14	-68	-26	3.88
Subcortical structures						
Left thalamus	NA	Thalamus	-16	-30	0	3.19

^aMost probable localization of the activation peak based on the probabilistic cytoarchitecture provided by Anatomy Toolbox v 1.7 (Eickhoff et al. 2005, 2007). Conventions are the same adopted in the Toolbox, apart from NA, which stands for not assigned.

^bCerebral regions comprised within the cluster. When available, we reported the cytoarchitectonic probabilistic assignment of each cerebral region that accounted for at least 5% of the extent of the cluster (see Eickhoff et al. 2005, 2007). If not available, we reported the anatomical region. Abbreviations: CG, calcarine gyrus; IPC, inferior parietal cortex; IP, intraparietal cortex; ITG, inferior temporal gyrus; MOG, middle occipital gyrus; MTG, middle temporal gyrus; SI, primary somatosensory cortex; SOG, superior occipital gyrus; SPL, superior parietal cortex. Other conventions are the same adopted in the Toolbox, apart from NA, which stands for not assigned.

^cStereotaxic coordinates in MNI space are reported in mm.

2001; Gazzola et al. 2007; Turella et al. 2009). Activation within the parietal cortex for mimed actions was confirmed by a recent study (Montgomery et al. 2007), which demonstrated that the same parietal regions are activated to a similar extent during the observation of communicative gestures (see also Lui et al. 2008; Schippers et al. 2009). Unfortunately, in these studies, a condition involving the observation of actions where the hand was interacting with real objects was not considered (Montgomery et al. 2007; Lui et al. 2008; Schippers et al. 2009). Therefore, these studies demonstrated a modulation within the AON with respect to different types of non object-directed actions but not between object-related and pantomimed actions.

A second consideration, which can be drawn from the present findings, was concerned to the aim of the present study, which was how the presence of a goal-object modulates activity within the AON. In this respect, Grèzes et al. (2003) investigated such type of modulation reporting that both types of actions, object-related and non object-related, elicited similar activation within the AON. But they did not report a differential effect during the observation for the 2 types of actions. In contrast to these findings, in the present study, we have demonstrated that it was the activity within the somatosensory component of the AON that was modulated by the presence/absence of a goal-object as the target of an observed action. A previous study by Buccino et al. (2001) seemed to indicate a differential involvement of the cortices around the anterior part of the intraparietal sulcus and within the postcentral gyrus (i.e., the somatosensory part of the AON) for the observation of object-related and non object-related actions. This pattern of activation was similar to what reported here (higher activation for object-related actions and lower/no activation for non object-related actions). However, as outlined

above, the pattern of activation reported by Buccino et al. (2001) might have been confounded by activity related to the mere presence of the object. Therefore, their results might reflect at least 3 different types of effect: a “motor simulation” effect within the parietal node of the AON, a canonical effect due to the presence of a graspable object within the same posterior parietal regions and a “somatosensory simulation” effect within the somatosensory part of the AON (probably BA 2), similar to that reported in the present study. From this perspective, the motor simulation effect seems to be chiefly related to differences in the motor properties of the goal of the action (such as kinematics or the goal itself). The canonical effect may act in concert with the action simulation process in order to help the understanding of observed movements based on the properties of the object, if visually present. In particular, during the perception of fully visible actions, the canonical effect may allow an immediate discrimination between object-related and non object-related actions. In our study, we demonstrated that it is possible to segregate such effects by eliminating the influence of differences in motor, object, and contextual information, in order to study selectively the somatosensory simulation effect.

Somatosensory Simulation of Action

Here, we provide compelling evidence that within the AON partially visible object-related and non object-related actions were coded differentially in terms of their somatosensory properties. Although previous human studies have demonstrated activation within BA 2 during the observation of actions (Oouchida et al. 2004; Dinstein et al. 2007; Gazzola et al. 2007; Gazzola and Keysers 2009; Schippers et al. 2009; Turella et al. 2009; for review, see Keysers et al. 2010 and for a meta-analysis, see Caspers et al. 2010), the first strong indication of

Table 3
Regions found activated for the positive interaction

Peak anatomical localization	Peak probabilistic cytoarchitecture ^a	Regions within the cluster ^b	x	y	z ^c	t value
Parietal cortex						
Left postcentral gyrus	BA 2: 40%	SI (BA 2)	-30	-40	52	4.27
Right postcentral gyrus	BA 2: 40%	SI (BA 2, BA 3a, BA 3b)	30	-36	48	3.77

^aMost probable localization of the activation peak based on the probabilistic cytoarchitecture provided by Anatomy Toolbox v 1.7 (Eickhoff et al. 2005, 2007). Conventions are the same adopted in the Toolbox, apart from NA, which stands for not assigned.

^bCerebral regions comprised within the cluster. When available, we reported the cytoarchitectonic probabilistic assignment of each cerebral region that accounted for at least 5% of the extent of the cluster (see Eickhoff et al. 2005, 2007).

^cStereotaxic coordinates in MNI space are reported in mm.

Table 4
Paired *t*-tests for PSC within regions of interest

ROI localization	Contrasts (<i>t</i> -values and <i>P</i> -values)			
	Grasping > pantomime	Object > no object	Grasping > object	Pantomime > no object
Left postcentral gyrus	$t_{18} = 3.821, P = 0.001$	$t_{18} = -1.385, P = 0.183$	$t_{18} = 7.618, P < 0.001$	$t_{18} = 3.766, P = 0.001$
Right postcentral gyrus	$t_{18} = 3.417, P = 0.003$	$t_{18} = -1.000, P = 0.331$	$t_{18} = 6.112, P < 0.001$	$t_{18} = 3.500, P = 0.003$

Note: Significantly different pairwise comparisons are reported in bold. See Table 3 for coordinates in MNI space.

a somatosensory simulation process during action observation has been reported in recent monkey neuroimaging (Raos et al. 2004; Raos et al. 2007; Evangelidou et al. 2009). These studies brought attention to the somatosensory component of the AON, which was generally neglected in human neuroimaging studies, probably because mirror neurons were discovered within cerebral regions having motor properties (for review, see Keysers et al. 2010). A recent meta-analysis by Caspers et al. (2010) demonstrates, beyond any doubt, the consistent involvement of somatosensory cortices—together with the other regions of the AON—during the observation of actions.

The evidence for a recruitment of the somatosensory cortices pointed to a simulation process related to the somatosensory properties of observed actions, which might be as important as motor simulation for recognizing and understanding actions. But, for this to be true, it might be necessary to reveal that activation within the somatosensory areas is modulated depending on the somatosensory properties of the observed actions. Our findings supported this prediction by demonstrating that BOLD activation within BA 2 was modulated by previous information regarding the nature of the goal of the observed action. This might suggest that the system has the ability to discriminate across different, but visually identical, actions based solely on previous knowledge regarding properties of the environment. This occurred even when their goal was not visually available to the observer, but the observer had previous knowledge of the somatosensory consequences of the seen action. Remember that the kinematics for both the object-related and non object-related observed actions were exactly the same, so this type of confound must be discarded as a potential explanation for our results.

Although the observation of object-related actions determined a level of activity that was higher than that observed for non object-related actions, the observation of non object-related actions still activated these regions. Therefore, it appeared that in humans these regions were sensitive, though

to a lesser extent, to actions in which no physical goal (i.e., the object) is present. Considering the properties of BA 2 that are devoted to the processing of higher order somatosensory information combining proprioceptive and tactile inputs (Kaas 2004a, 2004b), we are tempted to interpret such a differential effect in light of the differences in somatosensory properties related to the observed actions. Whereas the observation of object-related actions entails both the simulation of the proprioceptive and the tactile properties of the hand-object interaction (i.e., haptics), the coding of non object-related actions only recruits the proprioceptive information of the moving hand.

This is in line with a recent study by our group reporting a similar effect in the case of the observation of static images depicting fully visible actions within BA 2 (Pierno et al. 2009). Here, somatosensory activation was higher following the observation of a grasping action toward an object than for the observation of a pointing action toward the same object and a control condition involving a relaxed hand lying on a table. Similarly, our results demonstrated maximal activation within BA 2 for the simulation of an action involving both tactile and proprioceptive information. Interestingly, in the Pierno et al. (2009) study, the activation for the pointing condition was higher than that for the control condition, suggesting that somatosensory simulation was evident even for an object-related action involving only a specific position of the joints of the hand and no interaction with the object. Therefore, also the BA 2 modulation found in that experiment (Pierno et al. 2009) might be explained in terms of somatosensory differences between observed actions.

An alternative and complementary explanation for our results may come from the central role played by the somatosensory cortices in action prediction. As demonstrated by a recent study (Lamm et al. 2007), somatosensory cortices were recruited during a reaching range prediction task in which participants had to predict whether a target was reachable by an observed person. Interestingly, although no movement was observed, the somatosensory cortices were

recruited. This was taken as an evidence of their role in anticipating the somatosensory consequences of a potential action. Considering that in our study the final part of the observed action was not visible, it might well be that the somatosensory modulation reported here may subtend the prediction of the unseen somatosensory consequences of either manipulating an object or simply faking such movement. All in all, the present findings suggest the strong relevance of the somatosensory system in action simulation (see Keysers et al. 2010).

Ventral Premotor Cortex and Presence of the Object

A final consideration refers to the fact that both object-related and non object-related actions appear to be coded within the human ventral sector of premotor cortex. This finding contrasts with what has been previously reported within the monkey mirror neurons literature (Umiltà et al. 2001; Rizzolatti and Craighero 2004; Rizzolatti and Fabbri-Destro 2008).

Nevertheless, a recent study on mirror neurons seemed to support our results, showing that observing both motor acts, such as grasping and object, and pantomime of the same action activated mirror neurons within the F5 region (Kraskov et al. 2009). This latter report reconciles monkey neurophysiological data with the large amount of human neuroimaging results providing evidence of an involvement of the ventral premotor cortex in the processing of non object-related actions. This contrasts with the notion that this kind of processing is a unique characteristic of our species.

Conclusions

The present study reported new insights on the type of processing occurring within the human AON. The central advance was the demonstration that previous knowledge regarding the presence/absence of a goal-object modulated activity within the somatosensory component of this network. By manipulating this type of information, we revealed that the AON was able to generate a representation of an observed action on the basis of the somatosensory properties of the action goal, even when the most crucial part of the action (i.e., hand-object interaction) is not visible. A number of studies put forward the proposal that the human AON responded to both object-related and non object-related actions, suggesting that when a target-object is not present, the AON was still recruited. Here, we add to this literature revealing that the AON had the ability to discriminate and understand observed partially hidden actions only on the basis of the somatosensory aspects characterizing their goal (i.e., tactile and proprioceptive properties) rather than their perceived physical or motor features.

Supplementary Material

Supplementary material can be found at: <http://www.cercor.oxfordjournals.org/>

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