Psychological Research (2009) 73:486–498
DOI 10.1007/s00426-009-0232-4

ORIGINAL ARTICLE

Motor abstraction: a neuroscientific account of how action goals and intentions are mapped and understood

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Received: 5 December 2008 / Accepted: 5 February 2009 / Published online: 21 April 2009

Abstract Recent findings in cognitive neuroscience shed light on the existence of a common neural mechanism that could account for action and intention to understand abilities in humans and non-human primates. Empirical evidence on the neural underpinnings of action goals and on their ontogeny and phylogeny is introduced and discussed. It is proposed that the properties of the mirror neuron system and the functional mechanism describing them, embodied simulation, enabled pre-linguistic forms of action and intention understanding. Basic aspects of social cognition appear to be primarily based on the motor cognition that underpins one's own capacity to act, here defined as motor abstraction. On the basis of this new account of the motor system, it is proposed that intersubjectivity is the best conceived of as intercorporeity.

Introduction

Primates, and particularly human beings, are social animals whose cognitive development capitalizes upon the interaction with other conspecifics (adults, siblings, etc.). During social interactions, we manifest our inner intentions, dispositions and thoughts by means of overt behavior. We reciprocate this by trying to figure out what are the intentions, dispositions and thoughts of others, when witnessing their behavior. Detecting another agent's intentions, or other inner states, helps anticipating this agent's future actions, which may be cooperative, non-cooperative or even threatening. Accurate understanding and anticipation enable the observer to adjust her/his responses appropriately. Fundamental among social abilities is the capacity to accurately detect and understand the intentional conduct of others, to anticipate their upcoming actions, and to appropriately adjust one's own behavior.

The phylogenetic origins of this capacity and its development in ontogenesis are matters of debate in both comparative and developmental psychology.

From an evolutionary perspective, the traditional view claims the existence of a sharp cognitive discontinuity between humans and non-human primates. Humans supposedly understand others by means of their capacity to mind read, that is, to attribute a causal role to internal mental states. All other animal species would be confined to the observable causal aspects of reality, that is, would be basically just behavior readers. From an ontogenetic perspective, theories differ about how and when the supposed mind reading ability emerges during infant cognitive development.

Recent findings in cognitive neuroscience shed light on the existence of a common neural mechanism that could account for action and intention understanding abilities both in humans and in non-human primates. These findings revealed that the motor cortex, long confined to the mere role of action programming and execution, in fact, it plays a crucial role in complex cognitive abilities such as the understanding of the intentions and goals of actions.

In the present paper, I first review neuroscientific evidence on the neural underpinnings of action goals and on their ontogeny and phylogeny. In the second part, I clarify how the goals and intentions of basic actions can be understood, and discuss the relationship between action-control and action-understanding, by introducing mirror neurons and the notion of embodied simulation. I propose that basic aspects of social cognition appear to be primarily grounded

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on the motor cognition that underpins one's own capacity to act, here defined as "motor abstraction". On the basis of this new account of the motor system, it is proposed that intersubjectivity is the best conceived of as intercorporeity.

Movements, actions and their neural underpinnings

On a purely descriptive level, actions are elementary building blocks of reality for certain living organisms: some species of organisms have developed agent-detecting modules, and some of them also conceive of themselves as agents. Let us now define what an action is on a *conceptual* level. Let us begin by distinguishing movements, motor acts and actions.

Bodily movements are simple physical events, and they can be represented accordingly. Motor acts are movements that are goal-directed, i.e., which can meaningfully be described as directed toward a set of satisfaction conditions, but without necessarily being linked to an explicit and conscious representation of such conditions. As simple movements, they also do not have a consciously experienced reward-producing component (Rizzolatti, Fogassi, & Gallese, 2001, p. 668). Motor acts, such as grasping an object, can be chained in sequential patterns in order to attain an overarching, more distal goal (e.g., grasping a glass and bringing it to the mouth in order to attain the distal goal of drinking), thus constituting actions. At difference with movements, motor acts are not necessarily isomorphic to a specific movement: different movements can in fact attain the same goal.

Actions are a specific subset of goal-directed movements. They are a series of motor acts that are functionally integrated with a currently active representation[1] of a goal-state as leading to a reward. Simplest actions can coincide with motor acts. Therefore, similarly to motor acts, an action is not isomorphic to a particular movement or specific behavioral pattern, because many different movements can constitute the same goal-directed action (e.g., one can drink by bringing a glass to the mouth following different trajectories, as well as by sipping the liquid by a straw). What individuates an action is the set of satisfaction conditions defining the content of its goal-component as leading to a reward plus the special way in which it is causally linked to the actual event of overt movement generation.

What do we know about the neural underpinnings of motor acts and actions? This will be the target of next section.

The neural correlates of motor behavior

For decades, neurophysiology has been reluctant to be involved with any research program investigating the realm of the intentional/representational aspects of behavior. In particular, the target of neurophysiological research carried out in the motor system of non-human primates was, and by some researchers still is, uniquely focused on the study of a multilayered system characterized *exclusively* in terms of very elementary physical features such as force, direction and amplitude. However, even without any explicit commitment to investigate the possible cognitive entailments of the neural control of motor behavior, a series of empirical results almost forces us to cope with the previously neglected cognitive aspects of action and its control.

In the following part of this section and in the next one, I will illustrate empirical evidence that forcefully points to a crucial role played by *inter-action* in shaping, defining and constraining the representational aspects of the dynamic interplay between organisms and environment. To do so, I will introduce the neural properties of a sector of the premotor cortex of macaque monkeys studied in our lab since more than 20 years.

The most anterior region of the ventral premotor cortex of the macaque monkey controls hand and mouth movements (Hepp-Reymond, Hüsler, Maier, & Qi, 1994; Rizzolatti et al., 1981, 1988; Kurata, & Tanji, 1986). This sector, which has specific histochemical and cytoarchitectonic features, has been termed as area F5 (Matelli, Luppino, & Rizzolatti, 1985). A fundamental functional property of area F5 is that most of its neurons do not discharge in association with elementary movements, but are active during *motor acts* such as grasping, tearing, holding or manipulating objects (Rizzolatti et al., 1988).

What is coded in premotor area F5 is not simply a physical parameter of movement such as force or movement direction, but rather the relationship, in motor terms, between the agent and the target of the action. Furthermore, this relation is of a very special kind: a relation leading to success. A hand reaches for an object, it grasps it, or manipulates it. F5 neurons indeed become active only *if* a particular type of effector–object relation (e.g., hand–object) is executed until the relation leads to a different state (e.g., to take possession of a piece of food, to throw away an object, to break it, to bring it to the mouth, etc.). Particularly, interesting in this respect are grasping-related neurons that fire any time the monkey *successfully* grasps an object, regardless of the effector employed, be it any of his two hands, the mouth, or both (Rizzolatti et al., 1988; see also Rizzolatti, Fogassi and Gallese, 2000).

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[1] In the present chapter the notion of representation is used very differently from its standard meaning in classic cognitive science and analytic philosophy. It refers to a particular type of content, generated by the relations that our situated and inter-acting brain–body system instantiates with the world of others. Such content is pre-linguistic and pre-theoretical, but nevertheless has attributes normally and uniquely attributed to conceptual content. The pre-linguistic status of motor content does not preclude access to consciousness.

Motor abstraction: goal coding in the motor system

The independence between the nature of the effector involved and the end-state that the same effector is supposed to attain seems to suggest that the motor system contains an *abstract* kind of means-end representation.

A formal quantitative testing and validation of this hypothesis was recently carried out by Umiltà et al. (2008). In this study, hand-related neurons were recorded from premotor area F5 and the primary motor cortex (area F1) in monkeys trained to grasp objects using two different tools: "normal pliers" and "reverse pliers." These tools require opposite movements to grasp an object: with normal pliers, the hand has to be first opened and then closed, as when grasping is executed with the bare hand, while with reverse pliers the hand has to be first closed and then opened. The use of the two tools enabled to dissociate the neural activity related to hand movement from that related to the goal of the motor act.

All tested neurons in area F5 and half of neurons recorded from the primary motor cortex discharged in relation to the accomplishment of the goal of grasping—when the tool closed on the object—regardless of whether during this phase the hand opened or closed, that is, regardless of the movements employed to accomplish the goal. The data of Umiltà et al. (2008) indicate that goal coding structures the way the action is mapped in area F5 and, although to a minor extent, even in the primary motor cortex.

The presence of a specific neural format for motor acts *goal states*, in the motor system allows, for the one hand, for a much simpler selection of a particular motor act within a given context (Rizzolatti et al., 1988). When the motor act is either self-generated or externally driven, only a few representational neural elements need to be selected.

On the other hand, within the context of a *motor*, *interactive* code for goal states, motor acts aimed to a specific goal can be represented in the brain just as such, as goal-states, and not in the far less economical terms of the specification and control of individual movements. Thus, we have a neural format that generalizes across different instances in which a particular successful end-state of the organism (the goal state) can be achieved. In accord with information theory, the informational narrower state has been reached by getting rid of redundant information, such as the load of information about *all* the dynamic patterns, under which, a given motor act can be characterized.

Beyond purely motor neurons, which constitute the overall majority of all F5 neurons, area F5 contains also two categories of "visuo-motor" neurons. Neurons of both categories have motor properties that are indistinguishable from those of the above-described purely motor neurons, while they have peculiar "visual" properties. The first category is made by neurons responding to the presentation of objects of particular size and shape in absence of any detectable action aimed to them, either by the monkey or by the experimenter. These neurons have been defined as "canonical neurons" (Raos, Umilta, Fogassi, & Gallese, 2006; Rizzolatti, & Fadiga, 1998; Rizzolatti et al. 2000; Umiltà, Brochier, Spinks, & Lemon, 2007).

The second category is made by neurons that discharge when the monkey *observes* an action made by another individual and when it *executes* the same or a similar action. These latter visuo-motor neurones were called "mirror neurons", which will be addressed in the next sections (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996; for a review, see Gallese, Keysers, & Rizzolatti, 2004; Rizzolatti et al., 2001; Rizzolatti, & Craighero, 2004).

Let us have a closer look at "canonical neurons." Because most grasping actions are executed under visual guidance, a relationship has to be established between the most important relational features of 3D visual objects (their affordances) and the specific motor specifications they might engender *whenever* the individual is aiming at them. The appearance of a graspable object in the visual space will retrieve immediately the appropriate "motor schema" of the intended type of hand–object relation. This process, in neurophysiological terms, implies that the same neuron must be able not only to code the motor acts it is supposed to control, but also to respond to the situated visual features triggering them.

Indeed, "canonical neurons" respond to the visual presentation of objects of different size and shape in absence of any detectable movement of the monkey (Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Murata et al., 1997; Raos et al., 2006; Rizzolatti et al., 1988; Rizzolatti, Fogassi and Gallese, 2004; Umiltà et al., 2007). Very often, a strict congruence has been observed between the type of grip coded by a given neuron and the size or shape of the object effective in triggering its "visual" response. The most interesting aspect, however, is the fact that in a considerable percentage of neurons, a congruence is observed between the response during the execution of a specific type of grip, and the visual response to objects that, although differing in shape, nevertheless all "afford" the same type of grip that excites the neuron when executed (see Murata et al., 1997; Raos et al., 2006).

The first conclusion we can draw is that such canonical neurons contribute a *multimodal representation of an organism–object relation*.

The function of F5 canonical grasping neurons can therefore hardly be defined in purely sensory or motor terms alone. At this stage, object-representations seem to be processed in *relationally specified* terms (Gallese 2000a, b). Within the operational logic of such neural network, a series of physical entities, 3D objects, are identified, differentiated, and *represented* not in relation to their mere physical appearance, but in relation to the effect of the interaction with an acting agent. Such pragmatic type of object representation is specifically and exclusively coded under a distinct type of motor neural activity patterns, involving dynamic organism–object relations. The automatic activation of pragmatic representations during object observation does not exclude that the specific nature of a given motor task can differently modulate the activation of motor representations related to specific affordances. Especially, when the same object can afford different types of prehension according to the different usage, the same object can afford. This aspect is certainly prominent in our species (see Bub, Masson, & Cree, 2008; Tipper, Paul, & Hayes, 2006).

This evidence is also important because it sheds light on important aspects of how the brain maps intentional actions. The limited "vocabulary" (Rizzolatti et al., 1988; see also Gallese, Rochat, Cossu, & Sinigaglia, 2009; Rizzolatti, et al., 2004) of motor acts represented in area F5 of the macaque monkey suggests that the intentional character, the "aboutness" of the representational format of our mind could be deeply rooted in the intrinsic relational character of body action. The intrinsic relational functional architecture of primates' motor system likely scaffolded the development of more abstract and detached forms of intentionality, as those characterizing thought in our species. This highlights the intrinsic *intertwined character* of action, perception and cognition (Gallese, 2000b; see also Hurley, 1998).

Representational content cannot be fully explained without considering it as the result of the ongoing modeling process of an organism *as currently integrated with the object to be represented*, *by intending it*. This integration process between the representing organism and the represented object is articulated in a multiple fashion, e.g., by intending to explore it by moving the eyes, intending to hold it in the focus of attention, by intending to grasp it, and ultimately, by *thinking* about it (see Gallese, 2000b, Gallese, & Metzinger, 2003; see also Metzinger, 1993, 2000, 2002).

The intrinsic need of any organism to control its dynamic interaction with the environment also determines the way these interactions are modeled, hence represented. Nature seems to have operated during the course of evolution according to a principle of parsimony. The same *sensory-motor* circuits that control the ongoing activity of the organism within its environment also map objects and events (see below on mirror neurons) in that very same environment, thus defining and shaping their representational content. *Motor abstraction* thus embeds both the causal efficacy determining overt behavior and its representational content, *qua* causally efficient.

It is no coincidence that our representation of the world is a *model* of it that *must* incorporate our idiosyncratic way to interact with it. This stems from the peculiar and unique way the biological organisms are supposed to gain information about the world, that is, by transducing its energetic nature into neural action potentials, through a peculiar type of active interaction with the world, in turn, shaped by how living organisms' bodies are built and how the world is. Our take on the reality of the world cannot be but a *model of the world* just for that reason.

Mammals, because of the way they are, can only represent the world by modeling it. We have learned also that this model can be conceived of as an integrated dynamic interplay between situated organisms and their natural playground. From this, it follows that the representational content resulting from the use of neural information for control purposes, and that same neural information of both shares the same ontological status. It must be emphasized, however, that such equivalence only holds if we qualify neural information as shaped and determined by the peculiar nature of the organisms making use of it. To put it in different words, the producer and the repository of representational content is not the brain per se, but the brain–body system, by means of its interactions with the world of which it is a part.

Action goals: ontogeny and phylogeny

The neuroscientific data, so far presented, make it necessary to answer the following question. What is a goal? From a scientific point of view, no such things as goals exist in the world. All that exists are goal-representations, for instance, as previously shown, goal motor representations activated by biological nervous systems. Goal-representations are representations of goal-states. What functionally *makes* such a state, a goal-state, is the fact that its internal representation is structured along an axis of valence: It possesses a value *for* the system. A value is anything that is conducive to preserve an organism's integrity (e.g., homeostasis), to maintain integration on higher levels of complexity (e.g., cognitive development and social interaction), and to procreative success. Therefore, the reward system is a second important element of the way, in which a goal-representation can be implemented in a causally effective way. Goal-states imply values on the level of the individual organism, and values are made causally effective through the reward system.

It is interesting to note how infants differently construe goal-relatedness when witnessing the intentional actions of other individuals as opposed to physical events not involving human agents. When 18-month-old infants see a person slip and fail to complete an intended action, they imitate the intended action and not the actual movements that the actor made. However, if the action is displayed by a mechanical device, they fail to successfully reproduce it (Meltzoff, 1995). A further argument favoring the hypothesis that goal-relatedness is differently perceived by infants in social and physical event configurations is provided by some findings by Woodward, Sommerville, and Guajardo, (2001). These researchers have shown that 6-month-old infants react differently to observed grasping actions according to the biological (human hand) or artificial (mechanical claw) nature of the grasping agent. Only the former are considered as goal-directed actions. It appears, therefore, that infants' early propensity to attend to goals seems to be specific to human actors.

According to some theorists, specialized developmental mechanisms that are in place at birth (Baron-Cohen, 1994; Leslie, 1994; Premack, 1990), allow infants to interpret actions as goal-directed very early in life. Innate sensitivity to behavioral cues like animacy, self-propelledness, temporal contingency and equifinal variations of action would enable infants to ascribe goal-relatedness to the action of a wide range of entities, largely encompassing their experience-related knowledge.

In a similar vein, Gergely and Csibra's Teleological stance hypothesis (Csibra, Gergely, Birò, Koòs, & Brockbank, 1999; Csibra, Birò, Koòs, & Gergely, 2003; Gergely, Nàdasdy, Csibra, & Bìrò, 1995; Gergely, & Csibra, 2003), posits that by 9 months of age, infants are equipped with an inferential system applied to factual reality (action, goal-state and current situational constraints) for generating non-mentalistic goal-directed action representations. According to these authors, an action is represented as teleological only if it satisfies a *"principle of rational action",* stating that an action can be explained by its goal-state if the agent reaches its goal through the most efficient mean given the contextual constraints.

A different theoretical view—fully endorsed by the author of this paper—on the emergence of infants' goal-directed action interpretation, stresses the intrinsic link between action understanding and experience. Several scholars emphasize the constructional effect of observational and self-agentive experience on infants' understanding of actions' goal-relatedness (see Sommerville, & Woodward, 2005). In particular, infant research employing habituation/dishabituation paradigms showed that previous motor experience facilitates 3-month-old infants' perception of goal-directed actions performed by others (Sommerville, & Wooward, 2005). Moreover, 10-month-old infants' ability to construe an action representation as hierarchically organized toward a distal goal strictly depends on their ability to perform similarly structured action sequences (Sommerville, & Woodward, 2005).

Interestingly, congruency between the observed action and the observer's motor repertoire seems to be crucial for goal prediction. In a recent study, it has been shown that just like adults using their own action plans to anticipate the actions of others (Flanagan, & Johansson, 2003), infants produce proactive goal-directed eye movements when observing a placing action, only to the extent they can perform it (Falck-Ytter, Gredeback, & van Hofsten, 2006). The results of Sommerville and Woodward (2005) and Falck-Ytter et al. (2006) suggest that in the case of specific goal-related interactions (such as hand–object interactions typical for reaching and grasping), it is simpler and more plausible to construe infants' understanding of intentions in terms of their own motor knowledge than by calling on a "pure reason"-based inferential system such as that assumed by Gergely and Csibra's Teleological Stance hypothesis (Gallese et al., 2009).

Goal detection is thought to form the core ability of action understanding and social learning through imitation. Both adults (Baird, & Baldwin, 2001) and children represent actions as constituted by units hierarchically organized with respect to an overarching goal. Ten-month-old children share with adults the ability to parse actions in units whose boundaries correspond to the completion of a goal (Baldwin, Baird, Saylor, & Clark, 2001). Imitation tasks clearly reflect children's ability to represent actions' units as organized toward a distal goal. When asked to imitate the action of another person, preschoolers reproduce the higher order goal of the action (Bekkering, Wohlschläger, & Gattis, 2000). 18-month-old infants reproduce the goal they inferred from the failed attempts of a human demonstrator (Meltzoff, 1995). Carpenter, Call, and Tomasello (2005) showed that infants could flexibly interpret the goal of an observed sequence of movements according to the context and therefore re-enact either the goal of an observed action or the means by which it had been produced. Similarly, Gergely, Bekkering, and Kiràly, (2002) found that 14-month-old infants reproduce both observed means and goal only when the reason according to which the agent choose a specific means appeared to surpass children's knowledge. Underlying this cognitive flexibility is the fundamental ability to discriminate between means and ends.

Rochat, Serra, Fadiga, and Gallese, (2008) recently investigated the ability of macaque monkeys to evaluate and predict the goal-directed action of others. Non-human primates' ability to discriminate between means and end and to use contextual cues to evaluate the ecological validity of a chosen mean has been tested by adapting a looking-time paradigm previously used with human babies (Gergely et al. 1995). Results showed that macaque monkeys, similarly to 9 to 12-month-old human infants, detect the goal of an observed motor act and, according to the physical characteristics of the context, construe expectancies about the most likely action the agent will execute in a given context. This, however, is true only to the extent that observed motor acts are consonant to the observer's motor repertoire, whereas inadequate motor acts, non-goal-related movements, or unfamiliar goal-related motor acts do not allow any simulation and prediction.

It is reasonable to hypothesize that monkeys evaluate the observed acts by mapping them on their own motor neural substrate, through the activation of the mirror neuron system (see below). The results of Rochat et al. (2008) provide the first evidence for the presence through phylogeny of the ability to evaluate the contextual adequacy of an action directed to a particular motor goal.

These results reveal that non-human primates are endowed with the ability to understand the intentional meaning of others' behavior by relying upon visible behavioral cues; hence they seriously argue against the traditional dichotomous account of primate social cognition based on a sharp evolutionary discontinuity between behavior- and mind-readers (for a discussion of this point, see Gallese, & Umiltà, 2006; Gallese, 2007). It appears that motor behavior contains elements that can be detected and used to understand it and to construe predictions about it, without necessarily relying on mental representations in propositional format, certainly precluded to non-human primates (Gallese et al., 2009).

Altogether the results of Woodward, Sommerville and co-workers on human infants and those of Rochat et al., on macaque monkeys suggest that, in the case of specific goal-related interactions (such as hand–object interactions typical for reaching and grasping), the understanding of basic action intentions is based on the observer's own motor knowledge.

The neurophysiological discovery that goal-relatedness is the functional organizing principle of primates' motor systems provides a possible phylogenetic explanatory framework to these empirical findings, lending support to a deflationary, motor account of the development of intentional understanding (Gallese et al., 2009).

Mirror neurons in monkeys: the understanding of action goals and intentions

About 17 years ago, we discovered in the macaque monkey brain a class of premotor neurons that discharge not only when the monkey executes goal-related hand actions like grasping objects, but also when observing other individuals (monkeys or humans) executing similar actions. We called them "mirror neurons" (Gallese et al., 1996; Rizzolatti et al., 1996; see also Gallese, 2000a, b, 2001, 2003a, b, 2004). Neurons with similar properties were later discovered in a sector of the posterior parietal cortex reciprocally connected with area F5 (Fogassi et al., 2005; Gallese, Fadiga, Fogassi, & Rizzolatti, 2002a).

The observation of an object-related action leads to the activation of the same neural network active during its actual execution. Action observation causes in the observer the automatic simulated re-enactment of the same action. We proposed that this mechanism could be at the basis of a direct form of action understanding (Gallese et al., 1996; Rizzolatti et al., 1996; see also Gallese, 2000a, b, 2003b, Gallese et al., 2002a; Gallese, Ferrari, Kohler, & Fogassi, 2002b).

The relationship between action understanding and action simulation is even more evident in light of the results of two other studies carried out in our laboratory. In the first series of experiments, F5 mirror neurons were tested in two conditions. In the first condition, the monkey could see the entire action (e.g., a hand grasping action); in the second condition, the same action was presented, but its final critical part, that is, the hand–object interaction, was hidden. Therefore, in the hidden condition, the monkey only "knew" that the target object was present behind the occluder. The results showed that more than half of the recorded neurons responded also in the hidden condition (Umiltà et al., 2001).

These results seem to suggest that predictions or "motor inferences" about the goals of the behavior of others appear to be mediated by the activity of motor neurons coding the goal of the same actions in the observer's brain. Out of sight is not "out of mind" just because, by simulating the action, the gap can be filled.

Some transitive actions are characteristically accompanied by a specific sound. Often this particular sound enables us to understand what is going on even without any visual information about the action producing the sound. The perceived sound has the capacity to make an invisible action inferred, and therefore present and understood.

We showed that a particular class of F5 mirror neurons, "audio-visual mirror neurons", discharge not only when the monkey executes or observes a particular type of noisy action (e.g., breaking a peanut), but also when it just listen to the sound produced by the action (see Keysers et al., 2003; Kohler et al. 2002).

These "audio-visual mirror neurons" not only respond to the sound of actions, but also discriminate between the sounds of different actions. The actions, whose sounds maximally trigger the neurons' discharge when heard, are those also producing the strongest response when observed or executed. The activation of the premotor neural network normally controlling the execution of action "A" by sensory information related to the same action "A," be it visual or auditory, can be characterized as simulating action "A".

The multi-modally driven simulation of action goals instantiated by neurons situated in the ventral pre-motor cortex of the monkey, instantiates properties that are strikingly similar to the symbolic properties characteristic of human thought. The similarity with conceptual content is quite appealing: the same conceptual content ("the goal of action A") results from a multiplicity of states subsuming it, sounds, observed and executed actions. These states, in turn, are subsumed by differently triggered patterns of activations within a population of "audio-visual mirror neurons."

The *action simulation* embodied by audiovisual mirror neurons is indeed reminiscent of the use of predicates. The verb "to break" is used to convey a meaning that can be used in different contexts: "seeing someone breaking a peanut", "hearing someone breaking a peanut", "breaking a peanut." The predicate, similarly to the responses in audiovisual mirror neurons, does not change depending on the context to which it applies, or depending on the subject/agent performing the action. All that changes is the context the predicate refers to (Gallese, 2003c; Gallese, & Lakoff, 2005).

A major step forward in the research on mirror neurons consisted in the discovery that parietal mirror neurons not only code the goal of an executed/observed motor act, like grasping an object, but they also discriminate identical motor acts (like grasping) according to the final goal of the action in which the act is embedded (e.g., grasping an object to bring it to the mouth or into a container, Fogassi et al., 2005). Mirror neurons map integrated sequences of goal-related motor acts (grasping, holding, bringing, placing) so to obtain different and parallely chained sequences of motor acts properly assembled to accomplish a more distal goal-state. Each embedded motor acts appears to be facilitated by the previously executed one, reorganizing itself as to map the fulfillment of the overarching goal. These results suggest—at least at the level of basic actions—that the "prior intention" of eating or placing the food is also coded by parietal mirror neurons. Of course, this does not imply that monkeys explicitly represent prior intentions as such. Preliminary results show that similar properties are instantiated by F5 mirror neurons (Ferrari et al., 2006).

The general picture conveyed by these results is that the sensory-motor integration supported by the premotor-parietal mirror neurons system instantiates simulations of transitive actions utilized not only to generate and control goal-related behaviors, but also to map the goals and purposes of others' actions, by means of their simulation. This account does not entail an explicit declarative format. It is meaningful, implicit, and direct.

Mirroring mechanisms in humans

Several studies using different experimental methodologies and techniques have documented the existence of a common neural activation during action observation and execution also in the human brain (for review, see Gallese, 2003a, b, 2005a, b, 2006, 2007; Gallese et al., 2004; Rizzolatti et al., 2001; Rizzolatti, & Craighero, 2004).

Neuroimaging studies have demonstrated that the observation of actions activated the likely human homolog of the monkey areas in which mirror neurons were originally described. In humans, the lower part of the precentral gyrus, the posterior part of the inferior frontal gyrus (IFG), the rostral part of the inferior parietal lobule, and regions within the intraparietal sulcus are described as "forming the core of human mirror system" (Rizzolatti, & Craighero, 2004). During the observation/execution of mouth, hand, and foot-related acts, the activation of distinct cortical regions within the premotor and posterior parietal cortices reflect the presence of a coarse somatotopic organization, similar to the one found in monkeys' homolog areas (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Buccino et al., 2001). Similar results have been found using transcranial magnetic stimulation (TMS, see Rizzolatti, & Craighero, 2004). Furthermore, Fadiga et al. (2002) showed that listening to speech is associated with an increase of motor-evoked potentials recorded from the listener's tongue muscles when the presented words strongly involved tongue movements.

Experimental evidence seems to suggest that motor experience affects action perception (Flach, Knoblich, & Prinz, 2003) and that the involvement of the mirror neuron system during action observation is strictly correlated to species and individuals' motor history. Mirror areas are significantly more activated when observing goal-directed actions executed by conspecifics (Buccino et al. 2004a). Moreover, several neuroimaging studies underlined the formative role played by motor experience in modeling action comprehension (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005; Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006; Järveläinen, Schlurmann, & Hari, 2004). Those results corroborate the hypothesis that actions may be differently perceived—and understood—on the basis of the individual's motor capabilities and experience.

The existence of shared neural and cognitive representations of one's own and other's action could at least partially account for the human ability to imitate actions. fMRI evidence shows that mirror areas in humans are selectively activated during simple movements imitation (Iacoboni et al., 1999), and during imitation, learning of complex skills (Buccino et al., 2004a, b; Vogt et al., 2007). Buccino et al. (2004b) proposed that during learning of new motor patterns by imitation, the observed actions are decomposed into elementary motor acts that automatically activate the corresponding motor maps. The prefrontal cortex would then recombine the activated motor maps according to the observed model. A recent study by Buxbaum, Kyle and Menon (2005) on posterior parietal neurological patients with Ideomotor Apraxia has shown that they were not only disproportionately impaired in the imitation of transitive as compared to intransitive gestures, but they also showed a strong correlation between imitation deficits and the incapacity of recognizing observed goal-related meaningful hand actions.

We do not have a clear neuroscientific model of how humans can understand the intentions promoting the actions of others they observe. A given action can be originated by very different intentions. Suppose one sees someone else grasping a cup. Mirror neurons for grasping will most likely be activated in the observer's brain. A simple motor equivalence between the observed action and its motor representation in the observer's brain, however, can only tell us *what* the action is (its a grasp) and not *why* the action occurred. Determining why action A (grasping the cup) was executed, that is, determining its intention, can be equivalent to detecting the goal of the still not executed and impending subsequent action (say, drink from the cup).

In a fMRI study (Iacoboni et al., 2005), subjects watched three kinds of stimuli: grasping hand actions without a context, context only (a scene containing objects), and grasping hand actions embedded in contexts. In the latter condition, the context suggested the intention associated with the grasping action (either drinking or cleaning up). Actions embedded in contexts, compared with the other two conditions, yielded a significant signal increase in the posterior part of the IFG and the adjacent sector of the ventral premotor cortex, where hand actions are represented. Thus, premotor mirror areas—areas active during the execution and the observation of an action—previously thought to be involved only in action recognition are actually also involved in understanding the "why" of action, that is, the intention promoting it. Detecting the intention of Action A is equivalent to predict its distal goal, that is, the goal of the subsequent Action B.

Similarly to what observed in macaque monkeys (Fogassi et al., 2005), the mirror neuron system seems to be involved also in humans in the detection of action intentions. These results seem to suggest that even humans do not necessarily need to explicitly represent intentions as such when understanding them in others. Action intentions *are embedded* within the intrinsic intentionality of action, that is, its intrinsic relatedness to an end-state, a goal. Most of the time we do not *ascribe intentions to others*, we simply detect them. By means of embodied simulation, when witnessing others' behaviors, their motor intentional contents can be directly grasped without the need of representing them in propositional format.

Humans can easily detect the statistical frequency of action sequences as they are habitually performed or observed in the social environment. Such detection can therefore trigger preferential paths of motor inferences/predictions. It can be hypothesized that this can be accomplished by chaining different populations of mirror neurons coding not only the observed motor act, but also those that in a given context would normally follow. Ascribing intentions would therefore consist in predicting a forthcoming new goal. If this is true, it follows that one important difference between humans and monkeys could be the level of recursivity attained by the mirror neuron system in our species. According to this perspective, action prediction and the ascription of intentions are related phenomena, underpinned by the same functional mechanism. In contrast with what mainstream cognitive science would maintain, action prediction and the ascription of intentions do not belong to different cognitive realms. Both pertain to embodied simulation mechanisms underpinned by the activation of chains of logically related mirror neurons.

Embodied simulation

The notion of simulation is employed in many different domains, often with different, not necessarily overlapping, meanings. Simulation is a functional process that possesses certain content, typically focusing on possible states of its target object. In philosophy of mind, the notion of simulation has been used by proponents of the Simulation Theory of mind-reading (see Gallese, & Goldman, 1998; Goldman, 1989, 1992a, b, 1993a, b, 2000, 2005, 2006; Goldman, & Gallese, 2000; Gordon, 1986, 1995, 2000, 2005) to characterize the pretend state adopted by the attributer in order to understand another person's behavior. Basically, according to this view, we use our mind to put ourselves into the mental shoes of others.

At difference with standard accounts of Simulation Theory, I qualify simulation as *embodied* in order to characterize it as a mandatory, pre-rational, non-introspectionist functional mechanism. Simulation, as conceived of in the present paper, is therefore not necessarily the result of a willed and conscious cognitive effort, aimed at interpreting the intentions hidden in the overt—and supposedly intentionally opaque—behavior of others, but rather a basic functional mechanism of our brain.

The Folk-Psychological model of mind reading proposed by standard accounts of Simulation Theory (Goldman, 2006) does not apply to the pre-linguistic and non-metarepresentational character of embodied simulation (Gallese, 2003a, b, c, 2005a, b, 2006). My embodied simulation model is, in fact, challenging the notion that Folk-Psychology is the sole account of interpersonal understanding. Before and below mind reading is *intercorporeity*—the mutual resonance of intentionally meaningful motor behaviors—as the main source of knowledge, we directly gather about others (Gallese, 2007).

We should perhaps abandon the Cartesian view of the primacy of the Ego, and adopt a perspective emphasizing the fact that the Other is co-originally given as the Self. Both Self and Other appear to be intertwined because of the intercorporeity linking them. Self-individuation is a process originating from the necessity of disentangling the Self from the we-centric dimension, in which it is originally and constitutively embedded (Gallese, 2001, 2003a).

As recently emphasized by De Presteer (2008, p. 137) following Merleau-Ponty (1945), the body of intercorporeity is primarily perceived as a systematic means to go toward objects. This is the reason why, argues De Presteer "…the other is seen as a behavior and the "I" is primarily a "motor I" (2008, p. 137). Our own acting body thus becomes the main source of information about others' behavior. A direct form of understanding of others from within, as it were, is achieved by the activation of neural systems underpinning what others and we do.

Intercorporeity describes a crucial aspect of intersubjectivity not because the latter is phylogenetically and ontogenetically grounded on a mere similarity between our body and the body of others, but because we and others all share the same intentional objects and our situated motor systems are similarly wired to accomplish similar goals.

Parallel to the detached third-person sensory descriptions of the observed social stimuli, internal we-centric non-linguistic "motor representations" associated with actions are evoked in the observer, as if he or she were performing a similar action. By means of an isomorphic format, we can map others' actions onto our own motor representations. This is what I mean by embodied simulation when applied to the action domain.

To which extent embodied simulation is *solely* a motor phenomenon? According to the use I make of this notion, embodied simulation is not conceived of as being exclusively confined to the domain of motor control, but rather as a more general and basic endowment of our brain. Intercorporeity, it applies not only to actions or emotions, where the motor or viscero-motor components may predominate, but also to sensations like vision and touch. Indeed, it has been repeatedly shown that the same cortical areas activated by the experience of being touched on one's body also activate when witnessing the tactile experience of others (Blakemore et al., 2005; Ebisch et al., 2008; Keysers et al., 2004). On the basis of this evidence, I posit that embodied simulation is a crucial functional mechanism for empathy. It is mental because it has content (see Gallese, 2003c, 2005b). It is embodied not only because it is neurally realized, but also because it uses a pre-existing body-model in the brain realized by the sensory-motor system, and therefore involves a non-propositional form of self-representation.

The intentional attunement hypothesis

The mirror neuron systems and the other non-motor mirroring neural clusters in our brain mapping emotions and sensations represent a sub-personal instantiation of embodied simulation. With this mechanism, we do not just "see" an action, an emotion, or a sensation. Side by side with the sensory description of the observed social stimuli, internal representations of the body states associated with these actions, emotions, and sensations are evoked in the observer, 'as if' he/she would be doing a similar action or experiencing a similar emotion or sensation.

Social cognition is not *only* explicitly reasoning about the contents of someone else's mind. Our brains, and those of other primates, appear to have developed a basic functional mechanism, embodied simulation, which gives us an experiential insight of other minds. It must be added that the notion of neural mirroring and the related functional mechanism of embodied simulation do not imply that what is mirrored and simulated in the observer's brain needs to be an exact replica of its object. The mirror metaphor is perhaps misleading. The more we study mirroring mechanisms, the more we learn about their plasticity and dependence upon the personal history and situated nature of the "mirroring subject".

The phenomenal content of the intentional relations of others can be grasped by means of the activation of the mirroring mechanisms described here, which enables our "intentional attunement" to others. What turns the acting bodies inhabiting our social world into *goal-oriented selves* like us is not first and foremost an explicit inference by analogy, but the possibility of entertaining a "we-centric" shared meaningful interpersonal space. This shared manifold space (see Gallese, 2001, 2003a, b, 2005a, b) is enabled by embodied simulation, a specific functional mechanism, by means of which our brain/body system models its interactions with the world of others.

Intentional attunement, in turn, by mapping the others' intentions onto the observer's ones, produces the peculiar quality of familiarity we entertain with other individuals. This is what "being empathic" is about. By means of intentional attunement, the "objectual other" becomes "another self." The possibility to share the phenomenal content of intentional relations as mediated by sensory-motor multimodally integrated neural circuits, has interesting consequences—both from a theoretical and empirical point of view—on the debate on how semantics is mapped in the brain.

The picture conveyed by the neuroscientific data I reviewed here suggests the necessity to cut across the widely endorsed dichotomy between distinct semantic and pragmatic cognitive domains. According to this perspective, meaning is the outcome of our situated interactions with the world. Social meaning is primarily the object of practical concern, and not of theoretical judgment (see Millikan, 2004). It relies on non-inferential mechanisms, which do not require the explicit use of rationality. As proposed by Gordon (2005), the implicit recognition of conspecifics as intentional agents like oneself is a case of procedural rather than declarative knowledge.

This of course does not account for all of our social cognitive skills. Our most sophisticated mind reading abilities likely require the activation of large regions of our brain, certainly larger than a putative domain-specific Theory of Mind Module, as maintained by the standard cognitive account of mentalization. The same actions performed by others in different contexts can lead the observer to radically different interpretations. Thus, social stimuli are also understood on the basis of the explicit cognitive elaboration of their contextual aspects and of previous information. The point is that these two mechanisms are not mutually exclusive. Embodied simulation is experience-based, while the second mechanism is a cognitive description of an external state of affairs. When embodied simulation is not present or malfunctioning, as perhaps in autism (see Gallese, 2003b, 2006; Gallese et al., 2009), the propositional, more cognitively sophisticated mind reading abilities can—at best—only provide a pale, detached account of the social experiences of others.

Recently, there have been attempts to reconcile the evidence about mirroring mechanisms with the activation of frontal midline structures during mentalizing tasks. These attempts aim to an ecumenical or hybrid account of mentalization (see Uddin, Iacobani, Lange, & Keenan, 2007; Keysers, & Gazzola, 2007; Goldman, 2006). I think these attempts, although meritorious, are in principle open to the same criticism previously raised against the mainstream standard cognitive account of the "solipsistic representational mind." In fact, these attempts reify a Cartesian Self, supposedly the recipient of the outcome of the mentalizing process, by reducing it to the neural processing instantiated by a localized network of cortical areas such as midline areas and the temporo-parietal junction. Reductionism works if it is methodological, not if—as in these examples—becomes ontological. A further problem of these accounts derives from the fact that we are neither sure of the specific mind reading commitment of these brain structures[2] nor of the neurophysiological mechanisms underpinning such posited mind reading specificity.

The embodied simulation model is immune to these criticisms, first because it rests upon neural mechanisms that have been characterized at the single neuron level; second, because it postulates a situated Self that in virtue of the facticity of its pragmatic being-in-the-world, is constitutively "open to the other", to which is connected by means of the intrinsic relational architecture of the motor system. A Self whose proper development depends on the possibility of mirroring and being mirrored by the praxis of others. A Self that most of the time does not even "attribute" intentions to others, because these intentions are grasped as already embedded in the behavior of others.

The witnessed behavior of others triggers at the sub-personal level, the activation of mirroring neural networks, henceforth activating—at the functional level of the description—embodied simulation. It is an empirical issue to determine how much of social cognition, language included, can be explained by embodied simulation and its neural underpinnings.

This proposal also opens new interesting perspectives for the study of the neural underpinnings of psychopathological states (Gallese, 2003b, 2006) and psychotherapeutic relations (Gallese, 2008; Gallese et al., 2007), and of other aspects of intersubjectivity like esthetic experience (Freedberg, & Gallese, 2007).

Conclusions

Many scholars in the cognitive sciences exclusively focus on clarifying differences between humans and other primates with respect to the use of propositional attitudes. According to this mainstream view, humans have ToM, non-human primates do not. This paradigm so pervasive in contemporary cognitive science is too quick in establishing a direct and nomological link between our use of propositional attitudes and their supposed neural correlates. No one can deny that we use propositional attitudes, unless embracing a radical eliminativism (which is not my case). But it is perfectly possible that we will never find boxes in our brain containing the neural correlates of beliefs, desires and intentions as such. Such a search qualifies, in my opinion, as a heuristically poor form of ontological reductionism.

As pointed out by Allen and Bekoff (1997), this "all-or-nothing" approach to social cognition, this desperate search for a "mental Rubicon" (the wider the better) is strongly arguable. When trying to account for our cognitive abilities, we forget that they are the result of a long evolutionary process. It is reasonable to hypothesize that this evolutionary process proceeded along a line of continuity (see Gallese, & Goldman, 1998; Gallese et al., 2002a, b; Gallese, & Umiltà, 2006).

It is perhaps more fruitful to establish to which extent different cognitive strategies may be underpinned by similar functional mechanisms, which in the course of evolution acquire increasing complexity. The empirical data briefly reviewed in this chapter are an instantiation of this strategy

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[2] Recent evidence actually call into question the mind reading specificity of these cortical areas (see Bird et al., 2005; Mitchell, 2008)

of investigation. The data on mirror neurons in monkeys and mirroring circuits in the human brain seem to suggest that the ease with which we are capable to understand others and recognize them as similar to us—in other words, our "Intentional Attunement" to others—may rely on a series of mirroring mechanisms that we have just started to uncover.

Acknowledgments This work was supported by Ministero Italiano dell'Università e della Ricerca (MIUR) and by the EU grant NEST-COM and by the EU Marie Curie—Research Training Network 035975 "DISCOS—Disorders and coherence of the embodied self."

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