

THE MIRROR-NEURON SYSTEM

Giacomo Rizzolatti¹ and Laila Craighero²

¹*Dipartimento di Neuroscienze, Sezione di Fisiologia, via Volturno, 3, Università di Parma, 43100, Parma, Italy; email: giacomo.rizzolatti@unipr.it;*

²*Dipartimento SBTA, Sezione di Fisiologia Umana, via Fossato di Mortara, 17/19, Università di Ferrara, 44100 Ferrara, Italy; email: crh@unife.it*

Key Words mirror neurons, action understanding, imitation, language, motor cognition

■ **Abstract** A category of stimuli of great importance for primates, humans in particular, is that formed by actions done by other individuals. If we want to survive, we must understand the actions of others. Furthermore, without action understanding, social organization is impossible. In the case of humans, there is another faculty that depends on the observation of others' actions: imitation learning. Unlike most species, we are able to learn by imitation, and this faculty is at the basis of human culture. In this review we present data on a neurophysiological mechanism—the mirror-neuron mechanism—that appears to play a fundamental role in both action understanding and imitation. We describe first the functional properties of mirror neurons in monkeys. We review next the characteristics of the mirror-neuron system in humans. We stress, in particular, those properties specific to the human mirror-neuron system that might explain the human capacity to learn by imitation. We conclude by discussing the relationship between the mirror-neuron system and language.

INTRODUCTION

Mirror neurons are a particular class of visuomotor neurons, originally discovered in area F5 of the monkey premotor cortex, that discharge both when the monkey does a particular action and when it observes another individual (monkey or human) doing a similar action (Di Pellegrino et al. 1992, Gallese et al. 1996, Rizzolatti et al. 1996a). A lateral view of the monkey brain showing the location of area F5 is presented in Figure 1.

The aim of this review is to provide an updated account of the functional properties of the system formed by mirror neurons. The review is divided into four sections. In the first section we present the basic functional properties of mirror neurons in the monkey, and we discuss their functional roles in action understanding. In the second section, we present evidence that a mirror-neuron system similar to that of the monkey exists in humans. The third section shows that in humans, in addition to action understanding, the mirror-neuron system plays a fundamental role in action imitation. The last section is more speculative.

We present there a theory of language evolution, and we discuss a series of data supporting the notion of a strict link between language and the mirror-neuron system (Rizzolatti & Arbib 1998).

THE MIRROR-NEURON SYSTEM IN MONKEYS

F5 Mirror Neurons: Basic Properties

There are two classes of visuomotor neurons in monkey area F5: canonical neurons, which respond to the presentation of an object, and mirror neurons, which respond when the monkey sees object-directed action (Rizzolatti & Luppino 2001). In order to be triggered by visual stimuli, mirror neurons require an interaction between a biological effector (hand or mouth) and an object. The sight of an object alone, of an agent mimicking an action, or of an individual making intransitive (nonobject-directed) gestures are all ineffective. The object significance for the monkey has no obvious influence on the mirror-neuron response. Grasping a piece of food or a geometric solid produces responses of the same intensity.

Mirror neurons show a large degree of generalization. Presenting widely different visual stimuli, but which all represent the same action, is equally effective. For example, the same grasping mirror neuron that responds to a human hand grasping an object responds also when the grasping hand is that of a monkey. Similarly, the response is typically not affected if the action is done near or far from the monkey, in spite of the fact that the size of the observed hand is obviously different in the two conditions.

It is also of little importance for neuron activation if the observed action is eventually rewarded. The discharge is of the same intensity if the experimenter grasps the food and gives it to the recorded monkey or to another monkey introduced in the experimental room.

An important functional aspect of mirror neurons is the relation between their visual and motor properties. Virtually all mirror neurons show congruence between the visual actions they respond to and the motor responses they code. According to the type of congruence they exhibit, mirror neurons have been subdivided into "strictly congruent" and "broadly congruent" neurons (Gallese et al. 1996).

Mirror neurons in which the effective observed and effective executed actions correspond in terms of goal (e.g., grasping) and means for reaching the goal (e.g., precision grip) have been classed as "strictly congruent." They represent about one third of F5 mirror neurons. Mirror neurons that, in order to be triggered, do not require the observation of exactly the same action that they code motorically have been classed as "broadly congruent." They represent about two thirds of F5 mirror neurons.

F5 Mouth Mirror Neurons

The early studies of mirror neurons concerned essentially the upper sector of F5 where hand actions are mostly represented. Recently, a study was carried out on

the properties of neurons located in the lateral part of F5 (Ferrari et al. 2003), where, in contrast, most neurons are related to mouth actions.

The results showed that about 25% of studied neurons have mirror properties. According to the visual stimuli effective in triggering the neurons, two classes of mouth mirror neurons were distinguished: ingestive and communicative mirror neurons.

Ingestive mirror neurons respond to the observation of actions related to ingestive functions, such as grasping food with the mouth, breaking it, or sucking. Neurons of this class form about 80% of the total amount of the recorded mouth mirror neurons. Virtually all ingestive mirror neurons show a good correspondence between the effective observed and the effective executed action. In about one third of them, the effective observed and executed actions are virtually identical (strictly congruent neurons); in the remaining, the effective observed and executed actions are similar or functionally related (broadly congruent neurons).

More intriguing are the properties of the communicative mirror neurons. The most effective observed action for them is a communicative gesture such as lip smacking, for example. However, from a motor point of view they behave as the ingestive mirror neurons, strongly discharging when the monkey actively performs an ingestive action.

This discrepancy between the effective visual input (communicative) and the effective active action (ingestive) is rather puzzling. Yet, there is evidence suggesting that communicative gestures, or at least some of them, derived from ingestive actions in evolution (MacNeilage 1998, Van Hoof 1967). From this perspective one may argue that the communicative mouth mirror neurons found in F5 reflect a process of corticalization of communicative functions not yet freed from their original ingestive basis.

The Mirror-Neuron Circuit

Neurons responding to the observation of actions done by others are present not only in area F5. A region in which neurons with these properties have been described is the cortex of the superior temporal sulcus (STS; Figure 1) (Perrett et al. 1989, 1990; Jellema et al. 2000; see Jellema et al. 2002). Movements effective in eliciting neuron responses in this region are walking, turning the head, bending the torso, and moving the arms. A small set of STS neurons discharge also during the observation of goal-directed hand movements (Perrett et al. 1990).

If one compares the functional properties of STS and F5 neurons, two points emerge. First, STS appears to code a much larger number of movements than F5. This may be ascribed, however, to the fact that STS output reaches, albeit indirectly (see below), the whole ventral premotor region and not only F5. Second, STS neurons do not appear to be endowed with motor properties.

Another cortical area where there are neurons that respond to the observation of actions done by other individuals is area 7b or PF of Von Economo (1929) (Fogassi et al. 1998, Gallese et al. 2002). This area (see Figure 1) forms the rostral part of the

inferior parietal lobule. It receives input from STS and sends an important output to the ventral premotor cortex including area F5.

PF neurons are functionally heterogeneous. Most of them (about 90%) respond to sensory stimuli, but about 50% of them also have motor properties discharging when the monkey performs specific movements or actions (Fogassi et al. 1998, Gallese et al. 2002, Hyvarinen 1982).

PF neurons responding to sensory stimuli have been subdivided into “somatosensory neurons” (33%), “visual neurons” (11%), and “bimodal (somatosensory and visual) neurons” (56%). About 40% of the visually responsive neurons respond specifically to action observation and of them about two thirds have mirror properties (Gallese et al. 2002).

In conclusion, the cortical mirror neuron circuit is formed by two main regions: the rostral part of the inferior parietal lobule and the ventral premotor cortex. STS is strictly related to it but, lacking motor properties, cannot be considered part of it.

Function of the Mirror Neuron in the Monkey: Action Understanding

Two main hypotheses have been advanced on what might be the functional role of mirror neurons. The first is that mirror-neuron activity mediates imitation (see Jeannerod 1994); the second is that mirror neurons are at the basis of action understanding (see Rizzolatti et al. 2001).

Both these hypotheses are most likely correct. However, two points should be specified. First, although we are fully convinced (for evidence see next section) that the mirror neuron mechanism is a mechanism of great evolutionary importance through which primates understand actions done by their conspecifics, we cannot claim that this is the only mechanism through which actions done by others may be understood (see Rizzolatti et al. 2001). Second, as is shown below, the mirror-neuron system is the system at the basis of imitation in humans. Although laymen are often convinced that imitation is a very primitive cognitive function, they are wrong. There is vast agreement among ethologists that imitation, the capacity to learn to do an action from seeing it done (Thorndyke 1898), is present among primates, only in humans, and (probably) in apes (see Byrne 1995, Galef 1988, Tomasello & Call 1997, Visalberghi & Fragaszy 2001, Whiten & Ham 1992). Therefore, the primary function of mirror neurons cannot be action imitation.

How do mirror neurons mediate understanding of actions done by others? The proposed mechanism is rather simple. Each time an individual sees an action done by another individual, neurons that represent that action are activated in the observer's premotor cortex. This automatically induced, motor representation of the observed action corresponds to that which is spontaneously generated during active action and whose outcome is known to the acting individual. Thus, the mirror system transforms visual information into knowledge (see Rizzolatti et al. 2001).

Evidence in Favor of the Mirror Mechanism in Action Understanding

At first glance, the simplest, and most direct, way to prove that the mirror-neuron system underlies action understanding is to destroy it and examine the lesion effect on the monkey's capacity to recognize actions made by other monkeys. In practice, this is not so. First, the mirror-neuron system is bilateral and includes, as shown above, large portions of the parietal and premotor cortex. Second, there are other mechanisms that may mediate action recognition (see Rizzolatti et al. 2001). Third, vast lesions as those required to destroy the mirror neuron system may produce more general cognitive deficits that would render difficult the interpretation of the results.

An alternative way to test the hypothesis that mirror neurons play a role in action understanding is to assess the activity of mirror neurons in conditions in which the monkey understands the meaning of the occurring action but has no access to the visual features that activate mirror neurons. If mirror neurons mediate action understanding, their activity should reflect the meaning of the observed action, not its visual features.

Prompted by these considerations, two series of experiments were carried out. The first tested whether F5 mirror neurons are able to recognize actions from their sound (Kohler et al. 2002), the second whether the mental representation of an action triggers their activity (Umiltà et al. 2001).

Kohler et al. (2002) recorded F5 mirror neuron activity while the monkey was observing a noisy action (e.g., ripping a piece of paper) or was presented with the same noise without seeing it. The results showed that about 15% of mirror neurons responsive to presentation of actions accompanied by sounds also responded to the presentation of the sound alone. The response to action sounds did not depend on unspecific factors such as arousal or emotional content of the stimuli. Neurons responding specifically to action sounds were dubbed "audio-visual" mirror neurons.

Neurons were also tested in an experimental design in which two noisy actions were randomly presented in vision-and-sound, sound-only, vision-only, and motor conditions. In the motor condition, the monkeys performed the object-directed action that they observed or heard in the sensory conditions. Out of 33 studied neurons, 29 showed auditory selectivity for one of the two hand actions. The selectivity in visual and auditory modality was the same and matched the preferred motor action.

The rationale of the experiment by Umiltà et al. (2001) was the following. If mirror neurons are involved in action understanding, they should discharge also in conditions in which monkey does not see the occurring action but has sufficient clues to create a mental representation of what the experimenter does. The neurons were tested in two basic conditions. In one, the monkey was shown a fully visible action directed toward an object ("full vision" condition). In the other, the monkey saw the same action but with its final, critical part hidden ("hidden" condition). Before each trial, the experimenter placed a piece of food behind the screen so

that the monkey knew there was an object there. Only those mirror neurons were studied that discharged to the observation of the final part of a grasping movement and/or to holding.

Figure 2 shows the main result of the experiment. The neuron illustrated in the figure responded to the observation of grasping and holding (*A*, full vision). The neuron discharged also when the stimulus-triggering features (a hand approaching the stimulus and subsequently holding it) were hidden from monkey's vision (*B*, hidden condition). As is the case for most mirror neurons, the observation of a mimed action did not activate the neuron (*C*, full vision, and *D*, hidden condition). Note that from a physical point of view *B* and *D* are identical. It was therefore the understanding of the meaning of the observed actions that determined the discharge in the hidden condition.

More than half of the tested neurons discharged in the hidden condition. Out of them, about half did not show any difference in the response strength between the hidden- and full-vision conditions. The other half responded more strongly in the full-vision condition. One neuron showed a more pronounced response in the hidden condition than in full vision.

In conclusion, both the experiments showed that the activity of mirror neurons correlates with action understanding. The visual features of the observed actions are fundamental to trigger mirror neurons only inasmuch as they allow the understanding of the observed actions. If action comprehension is possible on another basis (e.g., action sound), mirror neurons signal the action, even in the absence of visual stimuli.

THE MIRROR-NEURON SYSTEM IN HUMANS

There are no studies in which single neurons were recorded from the putative mirror-neuron areas in humans. Thus, direct evidence for the existence of mirror neurons in humans is lacking. There is, however, a rich amount of data proving, indirectly, that a mirror-neuron system does exist in humans. Evidence of this comes from neurophysiological and brain-imaging experiments.

Neurophysiological Evidence

Neurophysiological experiments demonstrate that when individuals observe an action done by another individual their motor cortex becomes active, in the absence of any overt motor activity. A first evidence in this sense was already provided in the 1950s by Gastaut and his coworkers (Cohen-Seat et al. 1954, Gastaut & Bert 1954). They observed that the desynchronization of an EEG rhythm recorded from central derivations (the so-called mu rhythm) occurs not only during active movements of studied subjects, but also when the subjects observed actions done by others.

This observation was confirmed by Cochin et al. (1998, 1999) and by Altschuler et al. (1997, 2000) using EEG recordings, and by Hari et al. (1998) using

magnetoencephalographic (MEG) technique. This last study showed that the desynchronization during action observation includes rhythms originating from the cortex inside the central sulcus (Hari & Salmelin 1997, Salmelin & Hari 1994).

More direct evidence that the motor system in humans has mirror properties was provided by transcranial magnetic stimulation (TMS) studies. TMS is a non-invasive technique for electrical stimulation of the nervous system. When TMS is applied to the motor cortex, at appropriate stimulation intensity, motor-evoked potentials (MEPs) can be recorded from contralateral extremity muscles. The amplitude of these potentials is modulated by the behavioral context. The modulation of MEPs' amplitude can be used to assess the central effects of various experimental conditions. This approach has been used to study the mirror neuron system.

Fadiga et al. (1995) recorded MEPs, elicited by stimulation of the left motor cortex, from the right hand and arm muscles in volunteers required to observe an experimenter grasping objects (transitive hand actions) or performing meaningless arm gestures (intransitive arm movements). Detection of the dimming of a small spot of light and presentation of 3-D objects were used as control conditions. The results showed that the observation of both transitive and intransitive actions determined an increase of the recorded MEPs with respect to the control conditions. The increase concerned selectively those muscles that the participants use for producing the observed movements.

Facilitation of the MEPs during movement observation may result from a facilitation of the primary motor cortex owing to mirror activity of the premotor areas, to a direct facilitatory input to the spinal cord originating from the same areas, or from both. Support for the cortical hypothesis (see also below, Brain Imaging Experiments) came from a study by Strafella & Paus (2000). By using a double-pulse TMS technique, they demonstrated that the duration of intracortical recurrent inhibition, occurring during action observation, closely corresponds to that occurring during action execution.

Does the observation of actions done by others influence the spinal cord excitability? Baldissera et al. (2001) investigated this issue by measuring the size of the H-reflex evoked in the flexor and extensor muscles of normal volunteers during the observation of hand opening and closure done by another individual. The results showed that the size of H-reflex recorded from the flexors increased during the observation of hand opening, while it was depressed during the observation of hand closing. The converse was found in the extensors. Thus, while the cortical excitability varies in accordance with the seen movements, the spinal cord excitability changes in the opposite direction. These findings indicate that, in the spinal cord, there is an inhibitory mechanism that prevents the execution of an observed action, thus leaving the cortical motor system free to "react" to that action without the risk of overt movement generation.

In a study of the effect of hand orientation on cortical excitability, Maeda et al. (2002) confirmed (see Fadiga et al. 1995) the important finding that, in humans, intransitive movements, and not only goal-directed actions, determine

motor resonance. Another important property of the human mirror-neuron system, demonstrated with TMS technique, is that the time course of cortical facilitation during action observation follows that of movement execution. Gangitano et al. (2001) recorded MEPs from the hand muscles of normal volunteers while they were observing grasping movements made by another individual. The MEPs were recorded at different intervals following the movement onset. The results showed that the motor cortical excitability faithfully followed the grasping movement phases of the observed action.

In conclusion, TMS studies indicate that a mirror-neuron system (a motor resonance system) exists in humans and that it possesses important properties not observed in monkeys. First, intransitive meaningless movements produce mirror-neuron system activation in humans (Fadiga et al. 1995, Maeda et al. 2002, Patuzzo et al. 2003), whereas they do not activate mirror neurons in monkeys. Second, the temporal characteristics of cortical excitability, during action observation, suggest that human mirror-neuron systems code also for the movements forming an action and not only for action as monkey mirror-neuron systems do. These properties of the human mirror-neuron system should play an important role in determining the humans' capacity to imitate others' action.

Brain Imaging Studies: The Anatomy of the Mirror System

A large number of studies showed that the observation of actions done by others activates in humans a complex network formed by occipital, temporal, and parietal visual areas, and two cortical regions whose function is fundamentally or predominantly motor (e.g., Buccino et al. 2001; Decety et al. 2002; Grafton et al. 1996; Grèzes et al. 1998; Grèzes et al. 2001; Grèzes et al. 2003; Iacoboni et al. 1999, 2001; Koski et al. 2002, 2003; Manthey et al. 2003; Nishitani & Hari 2000, 2002; Perani et al. 2001; Rizzolatti et al. 1996b). These two last regions are the rostral part of the inferior parietal lobule and the lower part of the precentral gyrus plus the posterior part of the inferior frontal gyrus (IFG). These regions form the core of the human mirror-neuron system.

Which are the cytoarchitectonic areas that form these regions? Interpretation of the brain-imaging activations in cytoarchitectonic terms is always risky. Yet, in the case of the inferior parietal region, it is very plausible that the mirror activation corresponds to areas PF and PFG, where neurons with mirror properties are found in the monkeys (see above).

More complex is the situation for the frontal regions. A first issue concerns the location of the border between the two main sectors of the premotor cortex: the ventral premotor cortex (PMv) and the dorsal premotor cortex (PMd). In nonhuman primates the two sectors differ anatomically (Petrides & Pandya 1984, Tanné-Gariepy et al. 2002) and functionally (see Rizzolatti et al. 1998). Of them, PMv only has (direct or indirect) anatomical connections with the areas where there is visual coding of action made by others (PF/PFG and indirectly STS) and, thus, where there is the necessary information for the formation of mirror neurons (Rizzolatti & Matelli 2003).

On the basis of embryological considerations, the border between human PMd and PMv should be located, approximately, at Z level 50 in Talairach coordinates (Rizzolatti & Arbib 1998, Rizzolatti et al. 2002). This location derives from the view that the superior frontal sulcus (plus the superior precentral sulcus) represents the human homologue of the superior branch of the monkey arcuate sulcus. Because the border of monkey PMv and PMd corresponds approximately to the caudal continuation of this branch, the analogous border should, in humans, lie slightly ventral to the superior frontal sulcus.

The location of human frontal eye field (FEF) supports this hypothesis (Corbetta 1998, Kimming et al. 2001, Paus 1996, Petit et al. 1996). In monkeys, FEF lies in the anterior bank of the arcuate sulcus, bordering posteriorly the sector of PMv where arm and head movements are represented (area F4). If one accepts the location of the border between PMv and PMd suggested above, FEF is located in a similar position in the two species. In both of them, the location is just anterior to the upper part of PMv and the lowest part of PMd.

The other issue concerns IFG areas. There is a deeply rooted prejudice that these areas are radically different from those of the precentral gyrus and that they are exclusively related to speech (e.g., Grèzes & Decety 2001). This is not so. Already at the beginning of the last century, Campbell (1905) noted clear anatomical similarities between the areas of posterior IFG and those of the precentral gyrus. This author classed both the *pars opercularis* and the *pars triangularis* of IFG together with the precentral areas and referred to them collectively as the “intermediate precentral” cortex. Modern comparative studies indicate that the *pars opercularis* of IFG (basically corresponding to area 44) is the human homologue of area F5 (Von Bonin & Bailey 1947, Petrides & Pandya 1997). Furthermore, from a functional perspective, clear evidence has been accumulating in recent years that human area 44, in addition to speech representation, contains (as does monkey area F5) a motor representation of hand movements (Binkofski et al. 1999, Ehrsson et al. 2000, Gerardin et al. 2000, Iacoboni et al. 1999, Krams et al. 1998). Taken together, these data strongly suggest that human PMv is the homologue of monkey area F4, and human area 44 is the homologue of monkey area F5. The descending branch of the inferior precentral sulcus (homologue to the monkey inferior precentral dimple) should form the approximate border between the two areas (for individual variations of location and extension area 44, see Amunts et al. 1999 and Tomaiuolo et al. 1999).

If the homology just described is correct, one should expect that the observation of neck and proximal arm movements would activate predominantly PMv, whereas hand and mouth movements would activate area 44. Buccino et al. (2001) addressed this issue in an fMRI experiment. Normal volunteers were presented with video clips showing actions performed with the mouth, hand/arm, and foot/leg. Both transitive (actions directed toward an object) and intransitive actions were shown. Action observation was contrasted with the observation of a static face, hand, and foot (frozen pictures of the video clips), respectively.

Observation of object-related mouth movements determined activation of the lower part of the precentral gyrus and of the *pars opercularis* of the inferior frontal

gyrus (IFG), bilaterally. In addition, two activation foci were found in the parietal lobe. One was located in the rostral part of the inferior parietal lobule (most likely area PF), whereas the other was located in the posterior part of the same lobule. The observation of intransitive actions activated the same premotor areas, but there was no parietal lobe activation.

Observation of object-related hand/arm movements determined two areas of activation in the frontal lobe, one corresponding to the *pars opercularis* of IFG and the other located in the precentral gyrus. The latter activation was more dorsally located than that found during the observation of mouth movements. As for mouth movements, there were two activation foci in the parietal lobe. The rostral focus was, as in the case of mouth actions, in the rostral part of the inferior parietal lobule, but more posteriorly located, whereas the caudal focus was essentially in the same location as that for mouth actions. During the observation of intransitive movements the premotor activations were present, but the parietal ones were not.

Finally, the observation of object-related foot/leg actions determined an activation of a dorsal sector of the precentral gyrus and an activation of the posterior parietal lobe, in part overlapping with those seen during mouth and hand actions, in part extending more dorsally. Intransitive foot actions produced premotor, but not parietal, activation.

A weakness of the data by Buccino et al. (2001) is that they come from a group study. Data from single individuals are badly needed for a more precise somatotopic map. Yet, they clearly show that both the frontal and the parietal "mirror" regions are somatotopically organized. The somatotopy found in the inferior parietal lobule is the same as that found in the monkey. As far as the frontal lobe is concerned, the data appear to confirm the predictions based on the proposed homology. The activation of the *pars opercularis* of IFG should reflect the observation of distal hand actions and mouth actions, whereas that of the precentral cortex activation should reflect that of proximal arm actions and of neck movements.

It is important to note that the observation of transitive actions activated both the parietal and the frontal node of the mirror-neuron system, whereas the intransitive actions activated the frontal node only. This observation is in accord with the lack of inferior parietal lobule activation found in other studies in which intransitive actions were used (e.g., finger movements; Iacoboni et al. 1999, 2001; Koski et al. 2002, 2003). Considering that the premotor areas receive visual information from the inferior parietal lobule, it is hard to believe that the inferior parietal lobule was not activated during the observation of intransitive actions. It is more likely, therefore, that when an object is present, the inferior parietal activation is stronger than when the object is lacking, and the activation, in the latter case, does not reach statistical significance.

Brain Imaging Studies: Mirror-Neuron System Properties

As discussed above, the mirror-neuron system is involved in action understanding. An interesting issue is whether this is true also for actions done by individuals

belonging to other species. Is the understanding by humans of actions done by monkeys based on the mirror-neuron system? And what about more distant species, like dogs?

Recently, an fMRI experiment addressed these questions (Buccino et al. 2004). Video clips showing silent mouth actions performed by humans, monkeys, and dogs were presented to normal volunteers. Two types of actions were shown: biting and oral communicative actions (speech reading, lip smacking, barking). As a control, static images of the same actions were presented.

The results showed that the observation of biting, regardless of whether it was performed by a man, a monkey, or a dog, determined the same two activation foci in the inferior parietal lobule discussed above and activation in the *pars opercularis* of the IFG and the adjacent precentral gyrus (Figure 3). The left rostral parietal focus and the left premotor focus were virtually identical for all three species, whereas the right side foci were stronger during the observation of actions made by a human being than by an individual of another species. Different results were obtained with communicative actions. Speech reading activated the left *pars opercularis* of IFG; observation of lip smacking, a monkey communicative gesture, activated a small focus in the right and left *pars opercularis* of IFG; observation of barking did not produce any frontal lobe activation (Figure 4).

These results indicated that actions made by other individuals could be recognized through different mechanisms. Actions belonging to the motor repertoire of the observer are mapped on his/her motor system. Actions that do not belong to this repertoire do not excite the motor system of the observer and appear to be recognized essentially on a visual basis without motor involvement. It is likely that these two different ways of recognizing actions have two different psychological counterparts. In the first case the motor “resonance” translates the visual experience into an internal “personal knowledge” (see Merleau-Ponty 1962), whereas this is lacking in the second case.

One may speculate that the absence of the activation of the frontal mirror area reported in some experiments might be due to the fact that the stimuli used (e.g., light point stimuli, Grèzes et al. 2001) were insufficient to elicit this “personal” knowledge of the observed action.

An interesting issue was addressed by Johnson Frey et al. (2003). Using event-related fMRI, they investigated whether the frontal mirror activation requires the observation of a dynamic action or if the understanding of the action goal is sufficient. Volunteers were presented with static pictures of the same objects being grasped or touched. The results showed that the observation of the goals of hand-object interactions was sufficient to activate selectively the frontal mirror region.

In this experiment, *pars triangularis* of IFG has been found active in several subjects (see also Rizzolatti et al. 1996b, Grafton et al. 1996). In speech, this sector appears to be mostly related to syntax (Bookheimer 2002). Although one may be tempted to speculate that this area may code also the syntactic aspect of action (see Greenfield 1991), there is at present no experimental evidence in support of

this proposal. Therefore, the presence of activation of *pars triangularis* lacks, at the moment, a clear explanation.

Schubotz & Von Cramon (2001, 2002a,b) tested whether the frontal mirror region is important not only for the understanding of goal-directed actions, but also for recognizing predictable visual patterns of change. They used serial prediction tasks, which tested the participants' performance in a sequential perceptual task without sequential motor responses. Results showed that serial prediction caused activation in premotor and parietal cortices, particularly within the right hemisphere. The authors interpreted these findings as supporting the notion that sequential perceptual events can be represented independent of preparing an intended action toward the stimulus. According to these authors, the frontal mirror-neuron system node plays, in humans, a crucial role also in the representation of sequential information, regardless of whether it is perceptual or action related.

MIRROR-NEURON SYSTEM AND IMITATION

Imitation of Actions Present in the Observer's Repertoire

Psychological experiments strongly suggest that, in the cognitive system, stimuli and responses are represented in a commensurable format (Brass et al. 2000, Craighero et al. 2002, Wohlschlagler & Bekkering 2002; see Prinz 2002). When observers see a motor event that shares features with a similar motor event present in their motor repertoire, they are primed to repeat it. The greater the similarity between the observed event and the motor event, the stronger the priming is (Prinz 2002).

These findings, and the discovery of mirror neurons, prompted a series of experiments aimed at finding the neural substrate of this phenomenon (Iacoboni et al. 1999, 2001; Nishitani & Hari 2000, 2002).

Using fMRI, Iacoboni et al. (1999) studied normal human volunteers in two conditions: observation-only and observation-execution. In the "observation-only" condition, subjects were shown a moving finger, a cross on a stationary finger, or a cross on an empty background. The instruction was to observe the stimuli. In the "observation-execution" condition, the same stimuli were presented, but this time the instruction was to lift the right finger, as fast as possible, in response to them.

The most interesting statistical contrast was that between the trials in which the volunteers made the movement in response to an observed action (imitation) and the trials in which the movement was triggered by the cross. The results showed that the activity was stronger during imitation trials than during the other motor trials in four areas: the left *pars opercularis* of the IFG, the right anterior parietal region, the right parietal operculum, and the right STS region (see for this last activation Iacoboni et al. 2001). Further experiments by Koski et al. (2002) confirmed the importance of Broca's area, in particular when the action to be imitated had a specific goal. Grèzes et al. (2003) obtained similar results, but only

when participants had to imitate pantomimes. The imitation of object-directed actions surprisingly activated PMd.

Nishitani & Hari (2000, 2002) performed two studies in which they investigated imitation of grasping actions and of facial movements, respectively. The event-related MEG was used. The first study confirmed the importance of the left IFG (Broca's area) in imitation. In the second study (Nishitani & Hari 2002), the authors asked volunteers to observe still pictures of verbal and nonverbal (grimaces) lip forms, to imitate them immediately after having seen them, or to make similar lip forms spontaneously. During lip form observation, cortical activation progressed from the occipital cortex to the superior temporal region, the inferior parietal lobule, IFG (Broca's area), and finally to the primary motor cortex. The activation sequence during imitation of both verbal and nonverbal lip forms was the same as during observation. Instead, when the volunteers executed the lip forms spontaneously, only Broca's area and the motor cortex were activated.

Taken together, these data clearly show that the basic circuit underlying imitation coincides with that which is active during action observation. They also indicate that, in the posterior part of IFG, a direct mapping of the observed action and its motor representation takes place.

The studies of Iacoboni et al. (1999, 2001) showed also activations—superior parietal lobule, parietal operculum, and STS region—that most likely do not reflect a mirror mechanism. The activation of the superior parietal lobule is typically not present when subjects are instructed to observe actions without the instruction to imitate them (e.g., Buccino et al. 2001). Thus, a possible interpretation of this activation is that the request to imitate produces, through backward projections, sensory copies of the intended actions. In the monkey, superior parietal lobule and especially its rostral part (area PE) contains neurons that are active in response to proprioceptive stimuli as well as during active arm movements (Kalaska et al. 1983, Lacquaniti et al. 1995, Mountcastle et al. 1975). It is possible, therefore, that the observed superior parietal activation represents a kinesthetic copy of the intended movements. This interpretation fits well previous findings by Grèzes et al. (1998), who, in agreement with Iacoboni et al. (1999), showed a strong activation of superior parietal lobule when subjects' tasks were to observe actions in order to repeat them later.

An explanation in terms of sensory copies of the intended actions may also account for the activations observed in the parietal operculum and STS. The first corresponds to the location of somatosensory areas hidden in the sylvian sulcus (Disbrow et al. 2000), whereas the other corresponds to higher-order visual areas of the STS region (see above). Thus, these two activations might reflect somatosensory and visual copies of the intended action, respectively.

The importance of the *pars opercularis* of IFG in imitation was further demonstrated using repetitive TMS (rTMS), a technique that transiently disrupts the functions of the stimulated area (Heiser et al. 2003). The task used in the study was, essentially, the same as that of Iacoboni et al. (1999). The results showed that following stimulation of both left and right Broca's area, there was significant

impairment in imitation of finger movements. The effect was absent when finger movements were done in response to spatial cues.

Imitation Learning

Broadly speaking, there are two types of newly acquired behaviors based on imitation learning. One is substitution, for the motor pattern spontaneously used by the observer in response to a given stimulus, of another motor pattern that is more adequate to fulfill a given task. The second is the capacity to learn a motor sequence useful to achieve a specific goal (Rizzolatti 2004).

The neural basis of the capacity to form a new motor pattern on the basis of action observation was recently studied by Buccino et al. (G. Buccino, S. Vogt, A. Ritzl, G.R. Fink, K. Zilles, H.J. Freund & G. Rizzolatti, submitted manuscript), using an event-related fMRI paradigm. The basic task was the imitation, by naive participants, of guitar chords played by an expert guitarist. By using an event-related paradigm, cortical activation was mapped during the following events: (a) action observation, (b) pause (new motor pattern formation and consolidation), (c) chord execution, and (d) rest. In addition to imitation condition, there were three control conditions: observation without any motor request, observation followed by execution of a nonrelated action (e.g., scratching the guitar neck), and free execution of guitar chords.

The results showed that during the event observation-to-imitate there was activation of a cortical network that coincided with that which is active during observation-without-instruction-to-imitate and during observation in order not to imitate. The strength of the activation was, however, much stronger in the first condition. The areas forming this common network were the inferior parietal lobule, the dorsal part of PMv, and the *pars opercularis* of IFG. Furthermore, during the event observation-to-imitate, but not during observation-without-further-motor-action, there was activation of the superior parietal lobule, anterior mesial areas plus a modest activation of the middle frontal gyrus.

The activation during the pause event in imitation condition involved the same basic circuit as in event observation-of-the-same-condition, but with some important differences: increase of the superior parietal lobule activation, activation of PMd, and, most interestingly, a dramatic increase in extension and strength of the middle frontal cortex activation (area 46) and of the areas of the anterior mesial wall. Finally, during the execution event, not surprisingly, the activation concerned mostly the sensorimotor cortex contralateral to the acting hand.

These data show that the nodal centers for new motor pattern formation coincide with the nodal mirror-neuron regions. Although fMRI experiments cannot give information on the mechanism involved, it is plausible (see the neurophysiological sections) that during learning of new motor patterns by imitation the observed actions are decomposed into elementary motor acts that activate, via mirror mechanism, the corresponding motor representations in PF and in PMv and in the *pars opercularis* of IFG. Once these motor representations are activated,

they are recombined, according to the observed model by the prefrontal cortex. This recombination occurs inside the mirror-neuron circuit with area 46 playing a fundamental orchestrating role.

To our knowledge, there are no brain-imaging experiments that studied the acquisition of new sequences by imitation from the perspective of mirror neurons. Theoretical aspect of sequential learning by imitation and its possible neural basis have been discussed by Arbib (2002), Byrne (2002), and Rizzolatti (2004). The interested reader can find there an exhaustive discussion of this issue.

MIRROR-NEURON SYSTEM AND COMMUNICATION

Gestural Communication

Mirror neurons represent the neural basis of a mechanism that creates a direct link between the sender of a message and its receiver. Thanks to this mechanism, actions done by other individuals become messages that are understood by an observer without any cognitive mediation.

On the basis of this property, Rizzolatti & Arbib (1998) proposed that the mirror-neuron system represents the neurophysiological mechanism from which language evolved. The theory of Rizzolatti & Arbib belongs to theories that postulate that speech evolved mostly from gestural communication (see Armstrong et al. 1995, Corballis 2002). Its novelty consists of the fact that it indicates a neurophysiological mechanism that creates a common (parity requirement), nonarbitrary, semantic link between communicating individuals.

The mirror-neuron system in monkeys is constituted of neurons coding object-directed actions. A first problem for the mirror-neuron theory of language evolution is to explain how this close, object-related system became an open system able to describe actions and objects without directly referring to them.

It is likely that the great leap from a closed system to a communicative mirror system depended upon the evolution of imitation (see Arbib 2002) and the related changes of the human mirror-neuron system: the capacity of mirror neurons to respond to pantomimes (Buccino et al. 2001, Grèzes et al. 2003) and to intransitive actions (Fadiga et al. 1995, Maeda et al. 2002) that was absent in monkeys.

The notion that communicative actions derived from object-directed actions is not new. Vygotski (1934), for example, explained that the evolution of pointing movements was due to attempts of children to grasp far objects. It is interesting to note that, although monkey mirror neurons do not discharge when the monkey observes an action that is not object directed, they do respond when an object is hidden, but the monkey knows that the action has a purpose (Kohler et al. 2002). This finding indicates that breaking spatial relations between effector and target does not impair the capacity of understanding the action meaning. The precondition for understanding pointing—the capacity to mentally represent the action goal—is already present in monkeys.

A link between object-directed and communicative action was also stressed by other authors (see McNeilage 1998, Van Hoof 1967; for discussion of this link from the mirror neurons perspective, see above).

Mirror Neurons and Speech Evolution

The mirror neuron communication system has a great asset: Its semantics is inherent to the gestures used to communicate. This is lacking in speech. In speech, or at least in modern speech, the meaning of the words and the phono-articulatory actions necessary to pronounce them are unrelated. This fact suggests that a necessary step for speech evolution was the transfer of gestural meaning, intrinsic to gesture itself, to abstract sound meaning. From this follows a clear neurophysiological prediction: Hand/arm and speech gestures must be strictly linked and must, at least in part, share a common neural substrate.

A number of studies prove that this is true. TMS experiments showed that the excitability of the hand motor cortex increases during both reading and spontaneous speech (Meister et al. 2003, Seyal et al. 1999, Tokimura et al. 1996). The effect is limited to the left hemisphere. Furthermore, no language-related effect is found in the leg motor area. Note that the increase of hand motor cortex excitability cannot be attributed to word articulation because, although word articulation recruits motor cortex bilaterally, the observed activation is strictly limited to the left hemisphere. The facilitation appears, therefore, to result from a coactivation of the dominant hand motor cortex with higher levels of language network (Meister et al. 2003).

Gentilucci et al. (2001) reached similar conclusions using a different approach. In a series of behavioral experiments, they presented participants with two 3-D objects, one large and one small. On the visible face of the objects there were either two crosses or a series of dots randomly scattered on the same area occupied by the crosses. Participants were required to grasp the objects and, in the condition in which the crosses appeared on the object, to open their mouth. The kinematics of hand, arm, and mouth movements was recorded. The results showed that lip aperture and the peak velocity of lip aperture increased when the movement was directed to the large object.

In another experiment of the same study Gentilucci et al. (2001) asked participants to pronounce a syllable (e.g., GU, GA) instead of simply opening their mouth. It was found that lip aperture was larger when the participants grasped a larger object. Furthermore, the maximal power of the voice spectrum recorded during syllable emission was also higher when the larger object was grasped.

Most interestingly, grasping movements influence syllable pronunciation not only when they are executed, but also when they are observed. In a recent study (Gentilucci 2003), normal volunteers were asked to pronounce the syllables BA or GA while observing another individual grasping objects of different size. Kinematics of lip aperture and amplitude spectrum of voice was influenced by the grasping movements of the other individual. Specifically, both lip aperture and

voice peak amplitude were greater when the observed action was directed to larger objects. Control experiments ruled out that the effect was due to the velocity of the observed arm movement.

Taken together, these experiments show that hand gestures and mouth gestures are strictly linked in humans and that this link includes the oro-laryngeal movements used for speech production.

Auditory Modality and Mirror-Neuron Systems

If the meaning of manual gestures, understood through the mirror-neuron mechanism, indeed transferred, in evolution, from hand gestures to oro-laryngeal gestures, how did that transfer occur?

As described above, in monkeys there is a set of F5 mirror neurons that discharge in response to the sound of those actions that, when observed or executed by the monkey, trigger a given neuron (Kohler et al. 2002). The existence of these audio-visual mirror neurons indicates that auditory access to action representation is present also in monkeys.

However, the audio-visual neurons code only object-related actions. They are similar, in this respect, to the “classical” visual mirror neurons. But, as discussed above, object-related actions are not sufficient to create an efficient intentional communication system. Therefore, words should have derived mostly from association of sound with intransitive actions and pantomimes, rather than from object-directed actions.

An example taken from Paget (1930) may clarify the possible process at work. When we eat, we move our mouth, tongue, and lips in a specific manner. The observation of this combined series of motor actions constitutes the gesture whose meaning is transparent to everybody: “eat.” If, while making this action, we blow air through the oro-laryngeal cavities, we produce a sound like “mnyam-mnyam,” or “mnya-mnya,” words whose meaning is almost universally recognized (Paget 1930). Thus through such an association mechanism, the meaning of an action, naturally understood, is transferred to sound.

It is plausible that, originally, the understanding of the words related to mouth actions occurred through activation of audio-visual mirror neurons related to ingestive behavior (see Ferrari et al. 2003). A fundamental step, however, toward speech acquisition was achieved when individuals, most likely thanks to improved imitation capacities (Donald 1991), became able to generate the sounds originally accompanied by a specific action without doing the action. This new capacity should have led to (and derived from) the acquisition of an auditory mirror system, developed on top of the original audio-visual one, but which progressively became independent of it.

More specifically, this scenario assumes that, in the case discussed above, the premotor cortex became progressively able to generate the sound “mnyam-mnyam” without the complex motor synergies necessary for producing ingestive

action, and, in parallel, neurons developed able to both generate the sound and discharge (resonate) in response to that sound (echo-neurons). The incredibly confusing organization of Broca's area in humans, where phonology, semantics, hand actions, ingestive actions, and syntax are all intermixed in a rather restricted neural space (see Bookheimer 2002), is probably a consequence to this evolutive trend.

Is there any evidence that humans possess an echo-neuron system, i.e., a system that motorically "resonates" when the individual listens to verbal material? There is evidence that this is the case.

Fadiga et al. (2002) recorded MEPs from the tongue muscles in normal volunteers instructed to listen carefully to acoustically presented verbal and nonverbal stimuli. The stimuli were words, regular pseudowords, and bitonal sounds. In the middle of words and pseudowords either a double "f" or a double "r" were embedded. "F" is a labio-dental fricative consonant that, when pronounced, requires slight tongue mobilization, whereas "r" is linguo-palatal fricative consonant that, in contrast, requires a tongue movement to be pronounced. During the stimulus presentation the participants' left motor cortices were stimulated.

The results showed that listening to words and pseudowords containing the double "r" determines a significant increase of MEPs recorded from tongue muscles as compared to listening to words and pseudowords containing the double "f" and listening to bitonal sounds. Furthermore, the facilitation due to listening of the "r" consonant was stronger for words than for pseudowords.

Similar results were obtained by Watkins et al. (2003). By using TMS technique they recorded MEPs from a lip (*orbicularis oris*) and a hand muscle (first *interosseus*) in four conditions: listening to continuous prose, listening to nonverbal sounds, viewing speech-related lip movements, and viewing eye and brow movements. Compared to control conditions, listening to speech enhanced the MEPs recorded from the *orbicularis oris* muscle. This increase was seen only in response to stimulation of the left hemisphere. No changes of MEPs in any condition were observed following stimulation of the right hemisphere. Finally, the size of MEPs elicited in the first *interosseus* muscle did not differ in any condition.

Taken together these experiments show that an echo-neuron system exists in humans: when an individual listens to verbal stimuli, there is an activation of the speech-related motor centers.

There are two possible accounts of the functional role of the echo-neuron system. A possibility is that this system mediates only the imitation of verbal sounds. Another possibility is that the echo-neuron system mediates, in addition, speech perception, as proposed by Liberman and his colleagues (Liberman et al. 1967, Liberman & Mattingly 1985, Liberman & Wahlen 2000). There is no experimental evidence at present proving one or another of the two hypotheses. Yet, is hard to believe that the echo-system lost any relation with its original semantic function.

There is no space here to discuss the neural basis of action word semantics. However, if one accepts the evolutionary proposal we sketched above, there should be two roots to semantics. One, more ancient, is closely related to the action

mirror-neuron system, and the other, more recent, is based on the echo-mirror-neuron system.

Evidence in favor of the existence of the ancient system in humans has been recently provided by EEG and fMRI studies. Pulvermueller (2001, 2002) compared EEG activations while subjects listened to face- and leg-related action verbs (“walking” versus “talking”). They found that words describing leg actions evoked stronger in-going current at dorsal sites, close to the cortical leg-area, whereas those of the “talking” type elicited the stronger currents at inferior sites, next to the motor representation of the face and mouth.

In an fMRI experiment, Tettamanti et al. (M. Tettamanti, G. Buccino, M.C. Saccuman, V. Gallese, M. Danna, P. Scifo, S.F. Cappa, G. Rizzolatti, D. Perani & F. Fazio, submitted manuscript) tested whether cortical areas active during action observation were also active during listening to action sentences. Sentences that describe actions performed with mouth, hand/arm, and leg were used. The presentation of abstract sentences of comparable syntactic structure was used as a control condition. The results showed activations in the precentral gyrus and in the posterior part of IFG. The activations in the precentral gyrus, and especially that during listening to hand-action sentences, basically corresponded to those found during the observation of the same actions. The activation of IFG was particularly strong during listening of mouth actions, but was also present during listening of actions done with other effectors. It is likely, therefore, that, in addition to mouth actions, in the inferior frontal gyrus there is also a more general representation of action verbs. Regardless of this last interpretation problem, these data provide clear evidence that listening to sentences describing actions engages visuo-motor circuits subserving action representation.

These data, of course, do not prove that the semantics is exclusively, or even mostly, due to the original sensorimotor systems. The devastating effect on speech of lesions destroying the perisylvian region testifies the importance in action understanding of the system based on direct transformation of sounds into speech motor gesture. Thus, the most parsimonious hypothesis appears to be that, during speech acquisition, a process occurs somehow similar to the one that, in evolution, gave meaning to sound. The meaning of words is based first on the old nonverbal semantic system. Subsequently, however, the words are understood even without a massive activation of the old semantic system. Experiments, such as selective inhibition through TMS or electrical stimulation of premotor and parietal areas, are needed to better understand the relative role of the two systems in speech perceptions.

ACKNOWLEDGMENTS

This study was supported by EU Contract QLG3-CT-2002-00746, Mirror, EU Contract IST-2000-28159, by the European Science Foundation, and by the Italian Ministero dell'Università e Ricerca, grants Cofin and Fibr RBNEO1SZB4.

The *Annual Review of Neuroscience* is online at <http://neuro.annualreviews.org>

LITERATURE CITED

- Altschuler EL, Vankov A, Hubbard EM, Roberts E, Ramachandran VS, Pineda JA. 2000. Mu wave blocking by observation of movement and its possible use as a tool to study theory of other minds. *Soc. Neurosci.* 68.1 (Abstr.)
- Altschuler EL, Vankov A, Wang V, Ramachandran VS, Pineda JA. 1997. Person see, person do: human cortical electrophysiological correlates of monkey see monkey do cell. *Soc. Neurosci.* 719.17 (Abstr.)
- Amunts K, Schleicher A, Buergel U, Mohlberg H, Uylings HBM, Zilles K. 1999. Broca's region re-visited: cytoarchitecture and inter-subject variability. *J. Comp. Neurol.* 412: 319–41
- Arbib MA. 2002. Beyond the mirror system: imitation and evolution of language. In *Imitation in Animals and Artifacts*, ed. C Nehaniv, K Dautenhan, pp. 229–80. Cambridge MA: MIT Press
- Armstrong AC, Stokoe WC, Wilcox SE. 1995. *Gesture and the Nature of Language*. Cambridge, UK: Cambridge Univ. Press
- Baldissera F, Cavallari P, Craighero L, Fadiga L. 2001. Modulation of spinal excitability during observation of hand actions in humans. *Eur. J. Neurosci.* 13:190–94
- Binkofski F, Buccino G, Posse S, Seitz RJ, Rizzolatti G, Freund H. 1999. A fronto-parietal circuit for object manipulation in man: evidence from an fMRI-study. *Eur. J. Neurosci.* 11:3276–86
- Bookheimer S. 2002. Functional MRI of language: new approaches to understanding the cortical organization of semantic processing. *Annu. Rev. Neurosci.* 25:151–88
- Brass M, Bekkering H, Wohlschlagel A, Prinz W. 2000. Compatibility between observed and executed finger movements: comparing symbolic, spatial, and imitative cues. *Brain Cogn.* 44:124–43
- Buccino G, Binkofski F, Fink GR, Fadiga L, Fogassi L, et al. 2001. Action observation activates premotor and parietal areas in a somatotopic manner: an fMRI study. *Eur. J. Neurosci.* 13:400–4
- Buccino G, Lui F, Canessa N, Patteri I, Lagravinese G, et al. 2004a. Neural circuits involved in the recognition of actions performed by non-conspecifics: an fMRI study. *J. Cogn. Neurosci.* 16:1–14
- Byrne RW. 1995. *The Thinking Ape. Evolutionary Origins of Intelligence*. Oxford, UK: Oxford Univ. Press
- Byrne RW. 2002. Seeing actions as hierarchically organized structures: great ape manual skills. See Meltzoff & Prinz 2002, pp. 122–40
- Campbell AW. 1905. *Histological Studies on the Localization of Cerebral Function*. Cambridge, UK: Cambridge Univ. Press. 360 pp.
- Cochin S, Barthelemy C, Lejeune B, Roux S, Martineau J. 1998. Perception of motion and qEEG activity in human adults. *Electroencephalogr. Clin. Neurophysiol.* 107:287–95
- Cochin S, Barthelemy C, Roux S, Martineau J. 1999. Observation and execution of movement: similarities demonstrated by quantified electroencephalography. *Eur. J. Neurosci.* 11:1839–42
- Cohen-Seat G, Gastaut H, Faure J, Heuyer G. 1954. Etudes expérimentales de l'activité nerveuse pendant la projection cinématographique. *Rev. Int. Filmologie* 5:7–64
- Corballis MC. 2002. *From Hand to Mouth. The Origins of Language*. Princeton: Princeton Univ. Press. 257 pp.
- Corbetta M. 1998. Frontoparietal cortical networks for directing attention and the eye to visual locations: identical, independent, or overlapping neural systems? *Proc. Natl. Acad. Sci. USA* 95:831–38
- Craighero L, Bello A, Fadiga L, Rizzolatti G. 2002. Hand action preparation influences the responses to hand pictures. *Neuropsychologia* 40:492–502
- Decety J, Chaminade T, Grezes J, Meltzoff AN.

2002. A PET exploration of the neural mechanisms involved in reciprocal imitation. *Neuroimage* 15:265–72
- Di Pellegrino G, Fadiga L, Fogassi L, Gallese V, Rizzolatti G. 1992. Understanding motor events: a neurophysiological study. *Exp. Brain Res.* 91:176–80
- Disbrow E, Roberts T, Krubitzer L. 2000. Somatotopic organization of cortical fields in the lateral sulcus of homo sapiens: evidence for SII and PV. *J. Comp. Neurol.* 418:1–21
- Donald M. 1991. *Origin of the Modern Mind: Three Stages in the Evolution of Culture and Cognition*. Cambridge, MA: Harvard Univ. Press
- Ehrsson HH, Fagergren A, Jonsson T, Westling G, Johansson RS, Forssberg H. 2000. Cortical activity in precision- versus power-grip tasks: an fMRI study. *J. Neurophysiol.* 83:528–36
- Fadiga L, Craighero L, Buccino G, Rizzolatti G. 2002. Speech listening specifically modulates the excitability of tongue muscles: a TMS study. *Eur. J. Neurosci.* 15:399–402
- Fadiga L, Fogassi L, Pavesi G, Rizzolatti G. 1995. Motor facilitation during action observation: a magnetic stimulation study. *J. Neurophysiol.* 73:2608–11
- Ferrari PF, Gallese V, Rizzolatti G, Fogassi L. 2003. Mirror neurons responding to the observation of ingestive and communicative mouth actions in the monkey ventral premotor cortex. *Eur. J. Neurosci.* 17:1703–14
- Fogassi L, Gallese V, Fadiga L, Rizzolatti G. 1998. Neurons responding to the sight of goal directed hand/arm actions in the parietal area PF (7b) of the macaque monkey. *Soc. Neurosci.* 24:257.5 (Abstr.)
- Galef BG. 1988. Imitation in animals: history, definition and interpretation of data from psychological laboratory. In *Comparative Social Learning*, ed. T Zentall, BG Galef, pp. 3–28, Hillsdale, NJ: Erlbaum
- Gallese V, Fadiga L, Fogassi L, Rizzolatti G. 1996. Action recognition in the premotor cortex. *Brain* 119:593–609
- Gallese V, Fogassi L, Fadiga L, Rizzolatti G. 2002. Action representation and the inferior parietal lobule. In *Attention & Performance XIX. Common Mechanisms in Perception and Action*, ed. W Prinz, B Hommel, pp. 247–66. Oxford, UK: Oxford Univ. Press
- Gangitano M, Mottaghy FM, Pascual-Leone A. 2001. Phase specific modulation of cortical motor output during movement observation. *NeuroReport* 12:1489–92
- Gastaut HJ, Bert J. 1954. EEG changes during cinematographic presentation. *Electroencephalogr. Clin. Neurophysiol.* 6:433–44
- Gentilucci M. 2003. Grasp observation influences speech production. *Eur. J. Neurosci.* 17:179–84
- Gentilucci M, Benuzzi F, Gangitano M, Grimaldi S. 2001. Grasp with hand and mouth: a kinematic study on healthy subjects. *J. Neurophysiol.* 86:1685–99
- Gerardin E, Sirigu A, Lehericy S, Poline JB, Gaymard B, et al. 2000. Partially overlapping neural networks for real and imagined hand movements. *Cereb. Cortex* 10:1093–104
- Grafton ST, Arbib MA, Fadiga L, Rizzolatti G. 1996. Localization of grasp representations in humans by PET: 2. Observation compared with imagination. *Exp. Brain Res.* 112:103–11
- Grèzes J, Armony JL, Rowe J, Passingham RE. 2003. Activations related to “mirror” and “canonical” neurones in the human brain: an fMRI study. *Neuroimage* 18:928–37
- Grèzes J, Costes N, Decety J. 1998. Top-down effect of strategy on the perception of human biological motion: a PET investigation. *Cogn. Neuropsychol.* 15:553–82
- Grèzes J, Decety J. 2001. Functional anatomy of execution, mental simulation, observation, and verb generation of actions: a meta-analysis. *Hum. Brain Mapp.* 12:1–19
- Grèzes J, Fonlupt P, Bertenthal B, Delon-Martin C, Segebarth C, Decety J. 2001. Does perception of biological motion rely on specific brain regions? *Neuroimage* 13:775–85
- Greenfield PM. 1991. Language, tool and brain: the ontogeny and phylogeny of hierarchically organized sequential behavior. *Behav. Brain Sci.* 14:531–95

- Hari R, Forss N, Avikainen S, Kirveskari S, Salenius S, Rizzolatti G. 1998. Activation of human primary motor cortex during action observation: a neuromagnetic study. *Proc. Natl. Acad. Sci. USA* 95:15061–65
- Hari R, Salmelin R. 1997. Human cortical oscillations: a neuromagnetic view through the skull. *Trends Neurosci.* 20:44–49
- Heiser M, Iacoboni M, Maeda F, Marcus J, Mazziotta JC. 2003. The essential role of Broca's area in imitation. *Eur. J. Neurosci.* 17:1123–28
- Hyvarinen J. 1982. Posterior parietal lobe of the primate brain. *Physiol. Rev.* 62:1060–129
- Iacoboni M, Koski LM, Brass M, Bekkering H, Woods RP, et al. 2001. Reafferent copies of imitated actions in the right superior temporal cortex. *Proc. Natl. Acad. Sci. USA* 98:13995–99
- Iacoboni M, Woods RP, Brass M, Bekkering H, Mazziotta JC, Rizzolatti G. 1999. Cortical mechanisms of human imitation. *Science* 286:2526–28
- Jeannerod M. 1994. The representing brain. Neural correlates of motor intention and imagery. *Behav. Brain Sci.* 17:187–245
- Jellema T, Baker CI, Wicker B, Perrett DI. 2000. Neural representation for the perception of the intentionality of actions. *Brain Cogn.* 44:280–302
- Jellema T, Baker CI, Oram MW, Perrett DI. 2002. Cell populations in the banks of the superior temporal sulcus of the macaque monkey and imitation. See Meltzoff & Prinz 2002, pp. 267–90
- Johnson Frey SH, Maloof FR, Newman-Norlund R, Farrer C, Inati S, Grafton ST. 2003. Actions or hand-objects interactions? Human inferior frontal cortex and action observation. *Neuron* 39:1053–58
- Kalaska JF, Caminiti R, Georgopoulos AP. 1983. Cortical mechanisms related to the direction of two-dimensional arm movements: relations in parietal area 5 and comparison with motor cortex. *Exp. Brain Res.* 51:247–60
- Kimmig H, Greenlee MW, Gondan M, Schira M, Kassubek J, Mergner T. 2001. Relationship between saccadic eye movements and cortical activity as measured by fMRI: quantitative and qualitative aspects. *Exp. Brain Res.* 141:184–94
- Kohler E, Keysers C, Umiltà MA, Fogassi L, Gallese V, Rizzolatti G. 2002. Hearing sounds, understanding actions: action representation in mirror neurons. *Science* 297:846–48
- Koski L, Iacoboni M, Dubeau MC, Woods RP, Mazziotta JC. 2003. Modulation of cortical activity during different imitative behaviors. *J. Neurophysiol.* 89:460–71
- Koski L, Wohlschlagel A, Bekkering H, Woods RP, Dubeau MC. 2002. Modulation of motor and premotor activity during imitation of target-directed actions. *Cereb. Cortex* 12:847–55
- Krams M, Rushworth MF, Deiber MP, Frackowiak RS, Passingham RE. 1998. The preparation, execution and suppression of copied movements in the human brain. *Exp. Brain Res.* 120:386–98
- Lacquaniti F, Guigon E, Bianchi L, Ferraina S, Caminiti R. 1995. Representing spatial information for limb movement: role of area 5 in the monkey. *Cereb. Cortex* 5:391–409
- Lieberman AM, Cooper FS, Shankweiler DP, Studdert-Kennedy M. 1967. Perception of the speech code. *Psychol. Rev.* 74:431–61
- Lieberman AM, Mattingly IG. 1985. The motor theory of speech perception revised. *Cognition* 21:1–36
- Lieberman AM, Whalen DH. 2000. On the relation of speech to language. *Trends Cogn. Neurosci.* 4:187–96
- MacNeilage PF. 1998. The frame/content theory of evolution of speech production. *Behav. Brain Sci.* 21:499–511
- Maeda F, Kleiner-Fisman G, Pascual-Leone A. 2002. Motor facilitation while observing hand actions: specificity of the effect and role of observer's orientation. *J. Neurophysiol.* 87:1329–35
- Manthey S, Schubotz RI, von Cramon DY. 2003. Premotor cortex in observing erroneous action: an fMRI study. *Brain Res. Cogn. Brain Res.* 15:296–307

- Meister IG, Borojerdi B, Foltys H, Sparing R, Huber W, Topper R. 2003. Motor cortex hand area and speech: implications for the development of language. *Neuropsychologia* 41:401–6
- Meltzoff AN, Prinz W. 2002. *The Imitative Mind. Development, Evolution and Brain Bases*. Cambridge, UK: Cambridge Univ. Press
- Merleau-Ponty M. 1962. *Phenomenology of Perception*. Transl. C Smith. London: Routledge (From French)
- Mountcastle VB, Lynch JC, Georgopoulos A, Sakata H, Acuna C. 1975. Posterior parietal association cortex of the monkey: command functions for operations within extrapersonal space. *J. Neurophysiol.* 38:871–908
- Nishitani N, Hari R. 2000. Temporal dynamics of cortical representation for action. *Proc. Natl. Acad. Sci. USA* 97:913–18
- Nishitani N, Hari R. 2002. Viewing lip forms: cortical dynamics. *Neuron* 36:1211–20
- Paget R. 1930. *Human Speech*. London: Kegan Paul, Trench
- Patuzzo S, Fiaschi A, Manganotti P. 2003. Modulation of motor cortex excitability in the left hemisphere during action observation: a single and paired-pulse transcranial magnetic stimulation study of self- and non-self action observation. *Neuropsychologia* 41:1272–78
- Paus T. 1996. Location and function of the human frontal eye-field: a selective review. *Neuropsychologia* 34:475–83
- Perani D, Fazio F, Borghese NA, Tettamanti M, Ferrari S, et al. 2001. Different brain correlates for watching real and virtual hand actions. *Neuroimage* 14:749–58
- Perrett DI, Harries MH, Bevan R, Thomas S, Benson PJ, et al. 1989. Frameworks of analysis for the neural representation of animate objects and actions. *J. Exp. Biol.* 146:87–113
- Perrett DI, Mistlin AJ, Harries MH, Chitty AJ. 1990. Understanding the visual appearance and consequence of hand actions. In *Vision and Action: The Control of Grasping*, ed. MA Goodale, pp. 163–342. Norwood, NJ: Ablex
- Petit L, Orssaud C, Tzourio N, Crivello F, Berthoz A, Mazoyer B. 1996. Functional anatomy of a prelearned sequence of horizontal saccades in humans. *J. Neurosci.* 16:3714–26
- Petrides M, Pandya DN. 1984. Projections to the frontal cortex from the posterior parietal region in the rhesus monkey. *J. Comp. Neurol.* 228:105–16
- Petrides M, Pandya DN. 1997. Comparative architectonic analysis of the human and the macaque frontal cortex. In *Handbook of Neuropsychology*, ed. F Boller, J Grafman, pp. 17–58. New York: Elsevier. Vol. IX
- Prinz W. 2002. Experimental approaches to imitation. See Meltzoff & Prinz 2002, pp. 143–62
- Pulvermueller F. 2001. Brain reflections of words and their meaning. *Trends Cogn. Sci.* 5:517–24
- Pulvermueller F. 2002. *The Neuroscience of Language*. Cambridge, UK: Cambridge Univ. Press. 315 pp.
- Rizzolatti G. 2004. The mirror-neuron system and imitation. In *Perspectives on Imitation: From Mirror Neurons to Memes*, ed. S Hurley, N Chater. Cambridge, MA: MIT Press. In press
- Rizzolatti G, Arbib MA. 1998. Language within our grasp. *Trends Neurosci.* 21:188–94
- Rizzolatti G, Fadiga L, Fogassi L, Gallese V. 1996a. Premotor cortex and the recognition of motor actions. *Cogn. Brain Res.* 3:131–41
- Rizzolatti G, Fadiga L, Matelli M, Bettinardi V, Paulesu E, et al. 1996b. Localization of grasp representation in humans by PET: 1. Observation versus execution. *Exp. Brain Res.* 111:246–52
- Rizzolatti G, Fogassi L, Gallese V. 2001. Neurophysiological mechanisms underlying the understanding and imitation of action. *Nat. Rev. Neurosci.* 2:661–70
- Rizzolatti G, Fogassi L, Gallese V. 2002. Motor and cognitive functions of the ventral premotor cortex. *Curr. Opin. Neurobiol.* 12:149–54
- Rizzolatti G, Luppino G. 2001. The cortical motor system. *Neuron* 31:889–901
- Rizzolatti G, Luppino G, Matelli M. 1998.

- The organization of the cortical motor system: new concepts. *Electroencephalogr. Clin. Neurophysiol.* 106:283–96
- Rizzolatti G, Matelli M. 2003. Two different streams form the dorsal visual system. *Exp. Brain Res.* 153:146–57
- Salmelin R, Hari R. 1994. Spatiotemporal characteristics of sensorimotor neuromagnetic rhythms related to thumb movement. *Neuroscience* 60:537–50
- Schubotz RI, von Cramon DY. 2001. Functional organization of the lateral premotor cortex: fMRI reveals different regions activated by anticipation of object properties, location and speed. *Brain Res. Cogn. Brain Res.* 11:97–112
- Schubotz RI, von Cramon DY. 2002a. A blueprint for target motion: fMRI reveals perceived sequential complexity to modulate premotor cortex. *Neuroimage* 16:920–35
- Schubotz RI, von Cramon DY. 2002b. Predicting perceptual events activates corresponding motor schemes in lateral premotor cortex: an fMRI study. *Neuroimage* 15:787–96
- Seyal M, Mull B, Bhullar N, Ahmad T, Gage B. 1999. Anticipation and execution of a simple reading task enhance corticospinal excitability. *Clin. Neurophysiol.* 110:424–29
- Strafella AP, Paus T. 2000. Modulation of cortical excitability during action observation: a transcranial magnetic stimulation study. *NeuroReport* 11:2289–92
- Tanné-Gariepy J, Rouiller EM, Boussaoud D. 2002. Parietal inputs to dorsal versus ventral premotor areas in the monkey: evidence for largely segregated visuomotor pathways. *Exp. Brain Res.* 145:91–103
- Thorndyke EL. 1898. Animal intelligence: an experimental study of the associative process in animals. *Psychol. Rev. Monogr.* 2:551–53
- Tokimura H, Tokimura Y, Oliviero A, Asakura T, Rothwell JC. 1996. Speech-induced changes in corticospinal excitability. *Ann. Neurol.* 40:628–34
- Tomaiuolo F, MacDonald JD, Caramanos Z, Posner G, Chiavaras M, et al. 1999. Morphology, morphometry and probability mapping of the pars opercularis of the inferior frontal gyrus: an in vivo MRI analysis. *Eur. J. Neurosci.* 11:3033–46
- Tomaselmo M, Call J. 1997. *Primate Cognition*. Oxford, UK: Oxford Univ. Press
- Umiltà MA, Kohler E, Gallese V, Fogassi L, Fadiga L, et al. 2001. “I know what you are doing”: a neurophysiological study. *Neuron* 32:91–101
- Van Hoof JARAM. 1967. The facial displays of the catarrhine monkeys and apes. In *Primate Ethology*, ed. D Morris, pp. 7–68. London: Weidenfield & Nicolson
- Visalberghi E, Fragaszy D. 2001. Do monkeys ape? Ten years after. In *Imitation in Animals and Artifacts*, ed. K Dautenhahn, C Nehaniv. Boston, MA: MIT Press
- Von Bonin G, Bailey P. 1947. *The Neocortex of Macaca Mulatta*. Urbana: Univ. Ill. Press. 136 pp.
- Von Economo C. 1929. *The Cytoarchitectonics of the Human Cerebral Cortex*. London: Oxford Univ. Press. 186 pp.
- Vygotsky LS. 1934. *Thought and Language*. Cambridge, MA: MIT Press
- Watkins KE, Strafella AP, Paus T. 2003. Seeing and hearing speech excites the motor system involved in speech production. *Neuropsychologia* 41:989–94
- Whiten A, Ham R. 1992. On the nature and evolution of imitation in the animal kingdom: reappraisal of a century of research. In *Advances in the Study of Behavior*, ed. PBJ Slater, JS Rosenblatt, C Beer, M Milinski, pp. 239–83. San Diego: Academic
- Wohlschlagler A, Bekkering H. 2002. Is human imitation based on a mirror-neurone system? Some behavioural evidence. *Exp. Brain Res.* 143:335–41

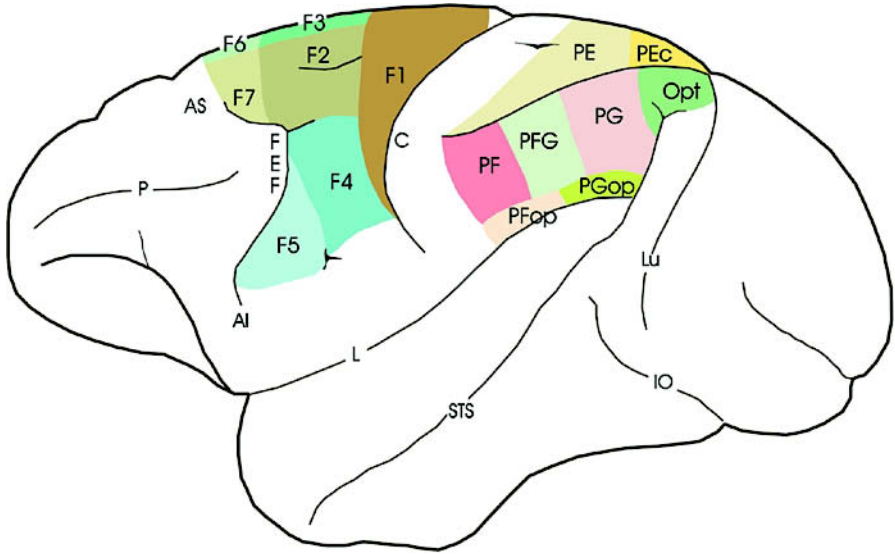


Figure 1 Lateral view of the monkey brain showing, in color, the motor areas of the frontal lobe and the areas of the posterior parietal cortex. For nomenclature and definition of frontal motor areas (F1–F7) and posterior parietal areas (PE, PEc, PF, PFG, PG, PF op, PG op, and Opt) see Rizzolatti et al. (1998). AI, inferior arcuate sulcus; AS, superior arcuate sulcus; C, central sulcus; L, lateral fissure; Lu, lunate sulcus; P, principal sulcus; POs, parieto-occipital sulcus; STS, superior temporal sulcus.

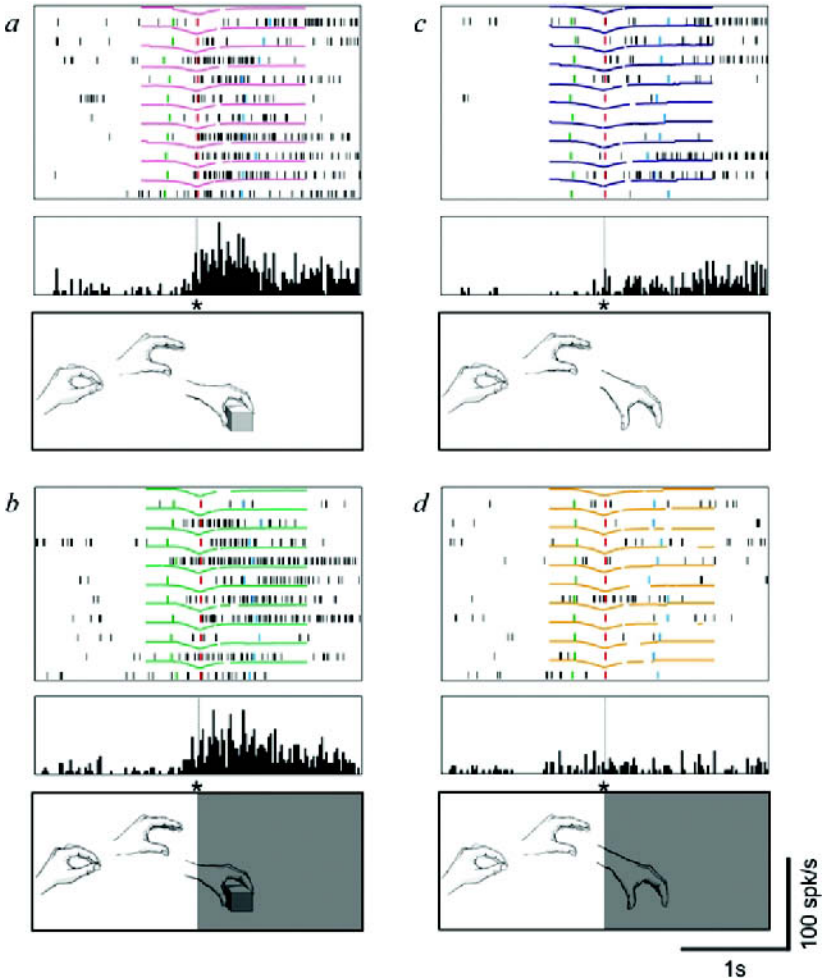


Figure 2 Mirror neuron responses to action observation in full vision (A and C) and in hidden condition (B and D). The lower part of each panel illustrates schematically the experimenter’s action as observed from the monkey’s vantage point. The asterisk indicates the location of a stationary marker attached to the frame. In hidden conditions the experimenter’s hand started to disappear from the monkey’s vision when crossing this marker. In each panel above the illustration of the experimenter’s hand, raster displays and histograms of ten consecutive trials recorded are shown. Above each raster, the colored line represents the kinematics of the experimenter’s hand movements expressed as the distance between the hand of the experimenter and the stationary marker over time. Rasters and histograms are aligned with the moment when the experimenter’s hand was closest to the marker. *Green vertical line*: movement onset; *red vertical line*: marker crossing; *blue vertical line*: contact with the object. Histograms bin width = 20 ms. The ordinate is in spike/s. (From Umiltà et al. 2001).

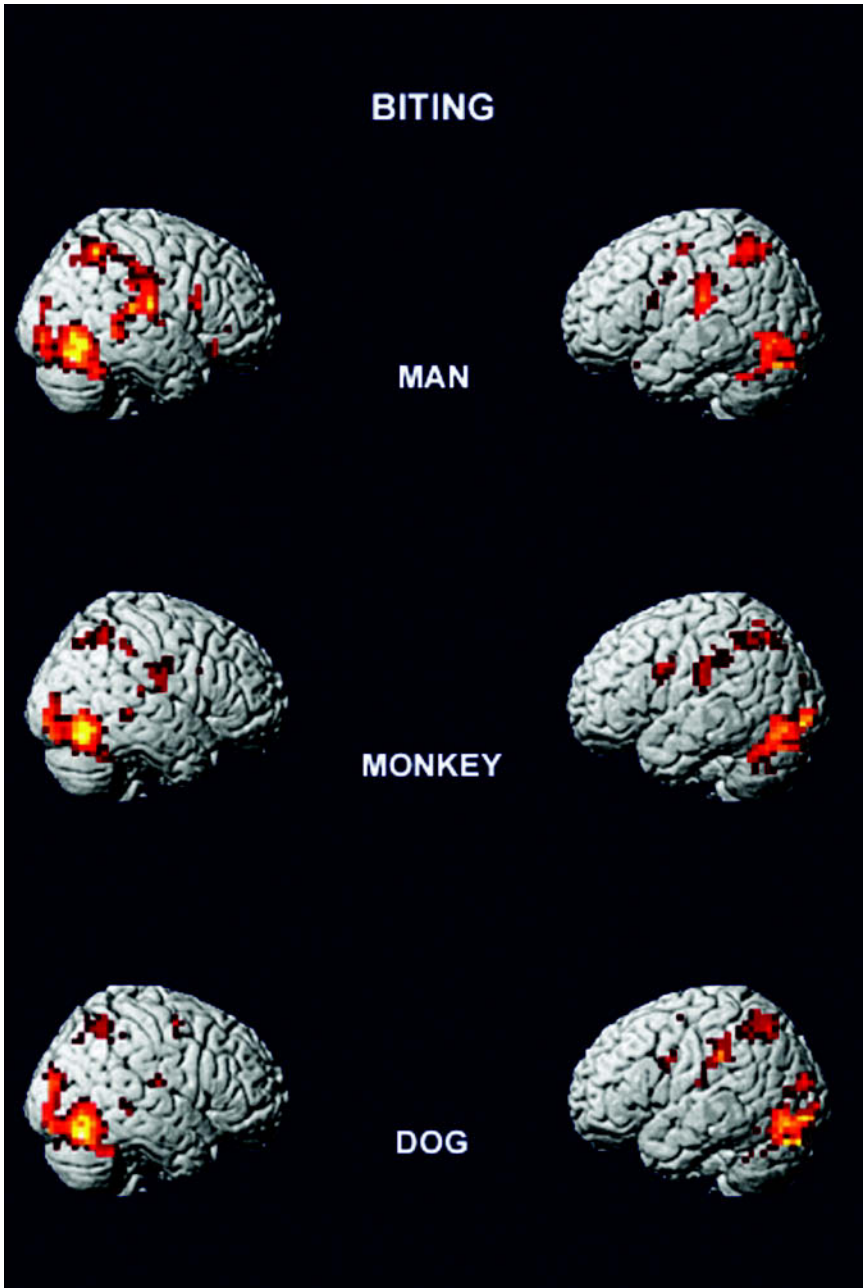


Figure 3 Cortical activations during the observation of biting made by a man, a monkey, and a dog. From Buccino et al. 2004.

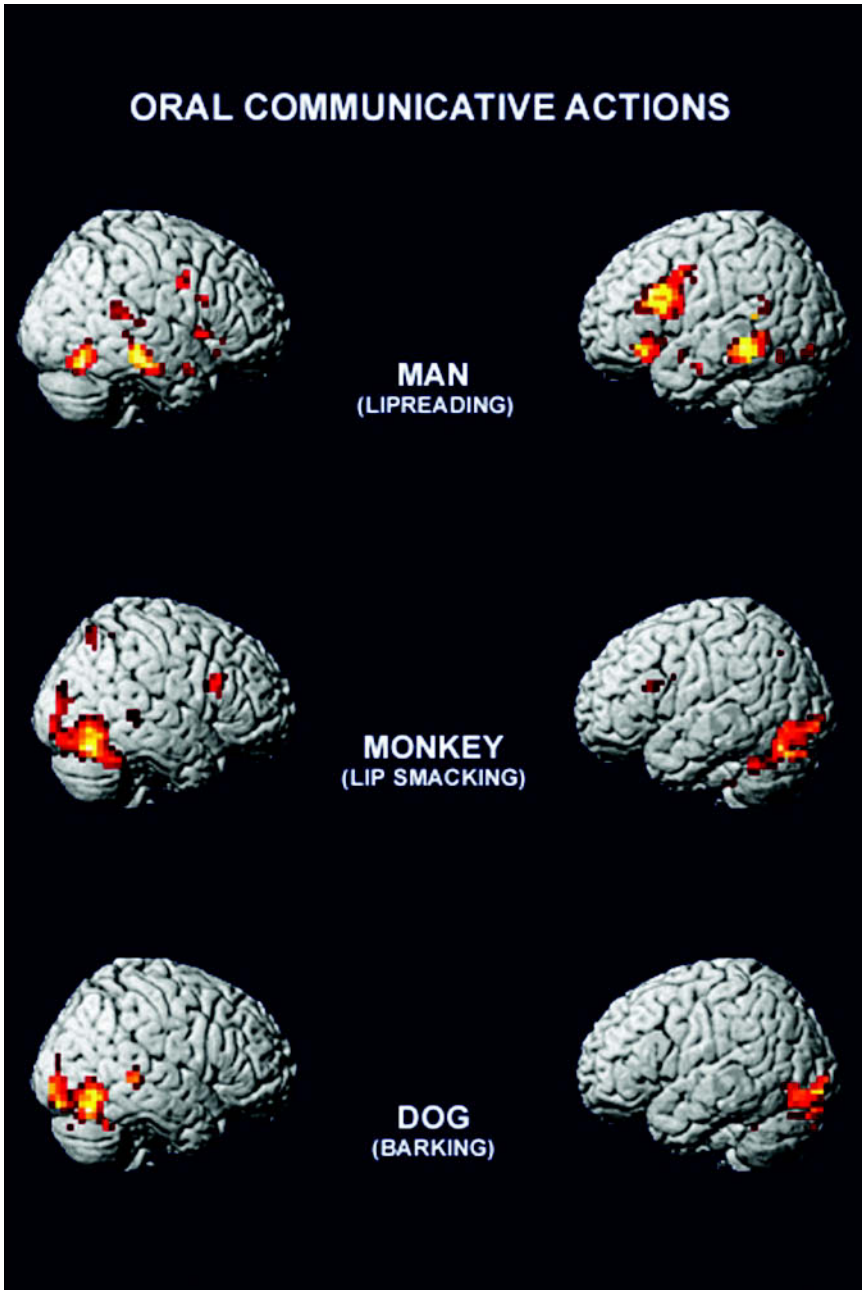


Figure 4 Cortical activations during the observation of communicative actions. For other explanations see text. From Buccino et al. 2004.



CONTENTS

THE AMYGDALA MODULATES THE CONSOLIDATION OF MEMORIES OF EMOTIONALLY AROUSING EXPERIENCES, <i>James L. McGaugh</i>	1
CONTROL OF CENTRAL SYNAPTIC SPECIFICITY IN INSECT SENSORY NEURONS, <i>Jonathan M. Blagburn and Jonathan P. Bacon</i>	29
SENSORY SIGNALS IN NEURAL POPULATIONS UNDERLYING TACTILE PERCEPTION AND MANIPULATION, <i>Antony W. Goodwin and Heather E. Wheat</i>	53
E PLURIBUS UNUM, EX UNO PLURA: QUANTITATIVE AND SINGLE-GENE PERSPECTIVES ON THE STUDY OF BEHAVIOR, <i>Ralph J. Greenspan</i>	79
DESENSITIZATION OF G PROTEIN-COUPLED RECEPTORS AND NEURONAL FUNCTIONS, <i>Raul R. Gainetdinov, Richard T. Premont, Laura M. Bohn, Robert J. Lefkowitz, and Marc G. Caron</i>	107
PLASTICITY OF THE SPINAL NEURAL CIRCUITRY AFTER INJURY, <i>V. Reggie Edgerton, Niranjala J.K. Tillakaratne, Allison J. Bigbee, Ray D. de Leon, and Roland R. Roy</i>	145
THE MIRROR-NEURON SYSTEM, <i>Giacomo Rizzolatti and Laila Craighero</i>	169
GENETIC APPROACHES TO THE STUDY OF ANXIETY, <i>Joshua A. Gordon and René Hen</i>	193
UBIQUITIN-DEPENDENT REGULATION OF THE SYNAPSE, <i>Aaron DiAntonio and Linda Hicke</i>	223
CELLULAR MECHANISMS OF NEURONAL POPULATION OSCILLATIONS IN THE HIPPOCAMPUS IN VITRO, <i>Roger D. Traub, Andrea Bibbig, Fiona E.N. LeBeau, Eberhard H. Buhl, and Miles A. Whittington</i>	247
THE MEDIAL TEMPORAL LOBE, <i>Larry R. Squire, Craig E.L. Stark, and Robert E. Clark</i>	279
THE NEURAL BASIS OF TEMPORAL PROCESSING, <i>Michael D. Mauk and Dean V. Buonomano</i>	307
THE NOGO SIGNALING PATHWAY FOR REGENERATION BLOCK, <i>Zhigang He and Vuk Koprivica</i>	341
MAPS IN THE BRAIN: WHAT CAN WE LEARN FROM THEM? <i>Dmitri B. Chklovskii and Alexei A. Koulakov</i>	369

ELECTRICAL SYNAPSES IN THE MAMMALIAN BRAIN, <i>Barry W. Connors and Michael A. Long</i>	393
NEURONAL CIRCUITS OF THE NEOCORTEX, <i>Rodney J. Douglas and Kevan A.C. Martin</i>	419
THE NEUROBIOLOGY OF THE ASCIDIAN TADPOLE LARVA: RECENT DEVELOPMENTS IN AN ANCIENT CHORDATE, <i>Ian A. Meinertzhagen, Patrick Lemaire, and Yasushi Okamura</i>	453
CORTICAL NEURAL PROSTHETICS, <i>Andrew B. Schwartz</i>	487
THE SYNAPTIC VESICLE CYCLE, <i>Thomas C. Südhof</i>	509
CRITICAL PERIOD REGULATION, <i>Takao K. Hensch</i>	549
CEREBELLUM-DEPENDENT LEARNING: THE ROLE OF MULTIPLE PLASTICITY MECHANISMS, <i>Edward S. Boyden, Akira Katoh, and Jennifer L. Raymond</i>	581
ATTENTIONAL MODULATION OF VISUAL PROCESSING, <i>John H. Reynolds and Leonardo Chelazzi</i>	611
THE HUMAN VISUAL CORTEX, <i>Kalanit Grill-Spector and Rafael Malach</i>	649
VISUAL MOTOR COMPUTATIONS IN INSECTS, <i>Mandyam V. Srinivasan and Shaowu Zhang</i>	679
HOW THE BRAIN PROCESSES SOCIAL INFORMATION: SEARCHING FOR THE SOCIAL BRAIN, <i>Thomas R. Insel and Russell D. Fernald</i>	697
UNRAVELING THE MECHANISMS INVOLVED IN MOTOR NEURON DEGENERATION IN ALS, <i>Lucie I. Bruijn, Timothy M. Miller, and Don W. Cleveland</i>	723
INDEXES	
Subject Index	751
Cumulative Index of Contributing Authors, Volumes 18–27	767
Cumulative Index of Chapter Titles, Volumes 18–27	772
ERRATA	
An online log of corrections to <i>Annual Review of Neuroscience</i> chapters may be found at http://neuro.annualreviews.org/	