RESONANCE BEHAVIORS AND MIRROR NEURONS

G. Rizzolatti, L. Fadiga, L. Fogassi And V. Gallese

Istituto di Fisiologia Umana, Università di Parma, Via Vollurno 39, 1-43100 Parma, Italy

Introduction

This article is formed by two parts. In the first part we discuss the functional properties of a monkey premotor area (area F5) and, specifically, those of an intriguing type of cortical neurons there located: the "mirror neurons" (11, 34). The second part is an attempt to give a neurophysiological account of behaviors in which an individual reproduces overtly or internally an action made by another individual. We will refer to these behaviors as "resonance behaviors".

The second part of our article is mostly speculative. We believe, however, that these speculations are not idle. Our hope is that a discussion of the various resonance behaviors could generate experiments that will throw light on mechanisms responsible for capabilities that are fundamental for social individuals such as understanding of actions made by others and their imitation.

An important lesson we learned from Professor Arduini by working for many years in strict contact with him is that the physiological experiments must be always thought in a broad theoretical framework. Only in this case they may acquire general significance. We are confident, therefore, that, although a considerable part of this article in his honor is speculative, he will be sympathetic with our efforts.

FUNCTIONAL PROPERTIES OF AREA F5

Motor properties

Area F5 forms the rostral part of inferior area 6 (24). Microstimulation and single neuron studies showed that F5 contains a hand and mouth movement representation (13, 18, 28, 33, 37). The two representations tend to be spatially segregated. Hand movements are mostly represented in the dorsal part of F5, while mouth movements are mostly located in its ventral part.

The properties of F5 "hand" neurons have been extensively investigated by Rizzolatti and coworkers (11, 27, 33, 37). They recorded single neuron activity in partially restrained monkeys trained to grasp and manipulate objects of different size and shape. They found that most of the "hand" neurons discharge in association with goal-directed actions such as grasping, manipulating, tearing, holding. F5 neurons do not discharge during finger and hand movements similar to those effective in triggering them when made with other purposes (e.g. pushing away). Virtually all of them discharge during action made both with the right and the left hand.

The class of neurons mostly represented in F5 is that of "grasping" neurons. Typically, these neurons discharge before the contact between the hand and the object, some of them stopping firing immediately after contact, others keeping firing for a while after it. The temporal relation between grasping movement and neuron discharge varies from neuron to neuron. Some neurons become active during the inilial phase of the moverment (opening of' the hand), some discharge

during hand closure and some others discharge during the entire grasping movement. from the beginning of fingers opening until their contact with the object.

Many grasping neurons discharge in association with a particular type of grip. Most of them are selective for one of the three most common grip types of the monkey: precision grip, finger prehension, whole hand grasping. A typical example of' a grasping neuron is shown in Figure 1. This neuron fires during precision grip (upper part of' the figure), but not during whole hand grasping (lower part of the figure). Note that the neuron discharges both when the animal grasps with its right and left hand.

Visual properties

The motor propert ies of' F5 that were just described are proper of all F5 neurons. There is, however, a certain percentage of them that respond to visual stimuli (27, 33). These visuomotor neurons fall into two separate categories. Neurons of the first category discharge when the monkey observes graspable objects. These neurons play a crucial role in object-to-hand movements transformations (see 19, see also below for further evidence). Because visuomotor transformation is one of the functions classically attributed to the ventral premotor cortex, we will refer to them as **"canonical F5 neurons"**. Neurons of the second category discharge when the monkey observes another individual making an action in front of it. These neurons will be referred to as "mirror neurons" (11, 34).

The two categories of F5 neurons are located in two different sub-regions of area F5: "canonical" neurons are mainly found in the posterior bank of arcuate sulcus, whereas "mirror" neurons are almost exclusively recorded from the cortical convexity of F5 (23).

Canonical neurons

The fundamental properties of canonical neurons can be summarized as follows. Canonical neurons respond to the presentation of 3-dimensional objects. In addition, many of them (more than 50%) are selective to objects of a particular size or orientation. Typically, there is a congruence between motor and visual selectivity. If a neuron discharges during "whole hand" prehension, if discharges also when the presented stimulus is large (ie. grasped using a whole hand prehension) but not when is small. Conversely, if a neuron discharges during precision grip, it discharges when the presented stimulus is small, but not when is large.

The response to object presentation is not conditional upon a successive action toward the object. This was proved by using a behavioral task in which the monkey was required to fixate an object and never to grasp if. At the presentation of a "go" signal, the monkey had to release a lever. If was found that also in this condition the canonical neurons responded to visual object presentation (27).

Finally, reversible inactivation of the posterior bank of the arcuate sulcus, the F5 sector where the canonical neurons are located, determines a severe deficit in the execution of' visually guided grasping movements. During inactivation, the monkey is unable to shape its hand in a way appropriate to the stimulus to be grasped and a correct grasp is obtained only after touching the stimulus on the basis of somatosensory information. The deficit is particularly evident in the case of precision grip (10).

Mirror neurons

The visual stimuli effective in triggering mirror neurons are actions in which the experimenter's hand or mouth interacts with objects. The responses evoked by these stimuli are highly consistent and do not habituate. The presentation of common visual objects, including

interesting stimuli such as food items, sight of faces or body movements are ineffective. Similarly, actions made using tools, even when very similar to those made using hands, do not activate or activate very weakly the neurons. Ineffective are also gestures having emotional meaning.

The observed hand actions which most frequently activate mirror neurons are grasping, placing and manipulating. The majority of mirror neurons become active only during the observation of a single action. Some are activated by two or three of them. Figure 2 shows an example of a grasping mirror neuron. Each trial started with stimulus presentation (a raisin placed on a tray). No discharge was prescrit. In A the stimulus was grasped by the experimenter. The neuron's discharge began during hand shaping and continued until the hand left the stimulus. No response was present during the phase subsequent to the grip when the tray with the food on it was moved toward the monkey. The neuron fired again when the monkey grasped the food. In B the same stimulus was grasped using a tool. In this condition only a weak discharge was elicited by action observation.

Figure 3 shows an example of a manipulating neuron. In A the monkey observed the experimenter taking out a raisin from a hole in a tray using his index finger. Each trial started with the presentation of the tray. The discharge began just before the experimenter's finger touched the food, and ceased when the food was retrieved from the hole. In B the experimenter mimicked the movement performed in A, but without an object. The neuron was only very weakly activated. In C the experimenter retrieved the stimulus with a tool. No response was evoked.

In most mirror neurons there is a clear relation between the visual action they respond to and the motor response they code. Using as classification criterion the congruence between the effective observed action and the effective executed action, we partitioned the mirror neurons into three broad classes: "strictly congruent", "broadly congruent", and "non congruent" (l 1).

As strictly congruent we defined those mirror neurons in which the effective observed and excetited actions correspond both in terms of general action (e.g. grasping) and in terms of the way in which that action was executed (e.g. precision grip). About 30% of the neurons fell in this group. We defined neurons as broadly congruent, when there was a similarity, but not identity, between the effective observed and executed action. Neurons with this type of congruence represented about 60% of the total of mirror neurons.

Finally, as non congruent we defined those neurons (about 8%) in which there was no clear-cut relationship between the effective observed action and the effective action of the monkey.

RESONANCE BEHAVIOR

There are many behaviors for which a "mirror" mechanism, similar to that described for F5 neurons, could represent the simplest (and most plausible) neural mechanism. We will refer to these behaviors as "resonance behaviors". We will posit that in resonance behavior a neural activity that is spontaneously generated during movements, gestures, or actions is also elicited when the individual observes another individual making similar movements, gestures and actions.

We will discuss two types of resonance behavior. One is that in which an individual repeats overtly, in a quasi automatic way, a movement made by another individual. The second is that in which an individual uses an internal motor template to repeat internally the actions made by others. This internal resonance may be used for an overt action, but its fundamental role is that of recognizing the observed action.

The two resonance behaviors may interact. For example, an individual may understand the goal of an action and try to achieve that goal. This can be obtained by repeating (or trying to repeat) the same movements that the actor of the action made or by making other movements

different from those employed by the actor. In the present article we will not deal with these more complex cases, but we will focus on the two resonance behaviors defined above. We will refer to them as resonance behavior of the first type and resonance behavior of second type, respectively.

Resonance behavior of the first type

We define as resonance behavior of the first type the tendency that individuals have to reproduce, immediately or with some delay, movements, gestures or actions made by another individual. The repeated actions and the conditions in which they are repeated vary very much. Yet, in spite of this heterogeneity, we propose that in all of them the basic mechanism is an activation of neurons that generate motor actions identical to those observed.

A typical example of a resonance behavior of the first type is the "imitative" behavior observed in many species of animals when one or a few of them start an action. One of the best studied examples is, probably, the behavior displayed by shore birds when alarmed. Typically, one or few birds start wing flapping, then others repeat it and, eventually, the whole flock turns in flight (42, 43). This "contagious" behavior does not require, necessarily, an "understanding" of the action. What is important here is only that the action emitted by the first bird could act as a "release" signal (43). A "resonance" of the motor system of the observing individual would be a simple and very advantageous mechanism for implementing this behavior.

Another example of the resonance behavior of the first type is represented by the capacity that some birds have to repeat the songs of conspecifics. There is convincing evidence that the neural mechanism at the basis of it is represented by neurons that discharge both when the bird produces a song and when it hears it (see 17 for review).

Resonance behavior of the first type appears to be present also in humans, in infants where it plays a fundamental role in establishing a communication with adults, and in adults as well.

An example of resonance behavior in infants is the capacity that even very young infants have of imitating buccal and manual gestures (25). It is hard to think that, at this early age, there is an understanding of the meaning of the observed gesture and a subsequent conscious desire to repeat it. A "resonance" mechanism of the first type appears to be the mechanism most likely underlying the phenomenon. This explanation appears particularly convincing in the case of facial gestures that the infant is able to imitate, in spite of the tact that it has never seen its own face.

There is, however, an important difference between the infant behavior and the "released" behavior of birds described above. As shown by Meltzoff and Moore (25; see also 26), when the infant response is artificially delayed, the behavior does not disappear as it should if it was simply a matter of response release, but is emitted subsequently when the response becomes possible. This difference is probably related to the presence in humans (as well as in most evolved species of animals) of mechanisms (see below) storing the externally evoked response and controlling its emission. Although these control mechanisms are not mature in infants - typically adults do not repeat overtly the observed gestures - still they appear to be already present in infants and allow a storage of the response and its delayed repetition.

As far as the aduilts are concerned, one has to distinguish actions related to emotional and vegetative life ("hot actions") from actions in which these components are limited or absent ("cold actions"). While adults usually do not repeat cold actions, an "imitation" frequently occurs in the case of hot actions. Smiling produces a tendency to respond with smiling. Similarly, adults and children alike **respond to the sight of an individual yawning by yawning themselve**s. Laughing is contagious. For all these actions there is no need to postulate a comprehension of the observed actions. The observed action simply releases in the observers the seen action. The term "response facilitation", proposed by Byrne (3) describes this behavior very well.

In contrast to normal adults, the repetition of "cold" action occurs in some severely demented patients. This behavior was named echopraxia. It is described as follows: (echopraxia) "is an impulsive or automatic imitation of other's people gestures, an imitation which is performed immediately with abruptness and speed of a reflex action. Irrespective of whether the gesture is natural or bizarre, helpful or dangerous, it is invariably reproduced" (7, 40).

It is likely that echopractic behavior represent a "release" of a covert resonance phenomenon of the first type present also in normal subjects, but inhibited in its expression by frontal and mesial cortical areas (21). Evidence that resonance phenomenon of the first type is present in normal subjects is provided by experiments in which evoked potentials were recorded from various arm muscles in normal subjects while they were observing hand and arm movements performed by an experimenter in front of them (8). The results showed a selective increase of motor evoked potentials in those muscles that the subjects normally use for producing the observed movements. The resonance phenomenon was present not only during observation of goal directed hand movements, but also during the observation of meaningless arm movements. These findings clearly show that the motor system "resonate" also in adult normal subjects, although the resonance is not sufficient to produce overt movements.

Another phenomenon due to the release of a cortical inhibition is the imitation behavior (21). This phenomenon, which is observed in frontal patients, especially in the case of fronto-orbital lesions, does not appear, however, to belong to resonance behavior of the first type. Unlike in echopraxia, patients with imitation behavior do not imitate the movements of the acting individual, but rather perform an action identical to the observed one. It is the goal rather than movements that is imitated in this pathology.

Resonance behavior of the second type
We define resonance behavior of the second type the activation of neurons coding motor actions during observation of similar actions made by others. While resonance behavior of the first type may be easily observed in humans and animals, the existence of a resonance phenomenon of the second type was the unexpected result of neurophysiological studies of area F5 of the monkey. The resonance behavior of the second type, although based as the first type on the activation of motor system in response to an observed action, differs from it for many important aspects.

First, unlike in the resonance behavior of the first type, the effect of the neural activity elicited by the observation of an action is not that of generating an overt motor response. A monkey looks at the action, and while looking at it, in its brain there is a motor replica of it. Yet the monkey does not repeat the seen action.

In an experiment we placed a second monkey in front of that from which action potentials were recorded. We then gave food to the newcomer taking it from a container. In this condition there was no obvious reason for the observing monkey (that from which we recorded) to repeat the gestures of the newcomer. The appropriate response was to jump on it and chase it away. Yet, the F5 mirror neurons fired any time the newcomer grasped the food (34).

Second, if the aim of the resonance phenomenon in F5 were that of allowing the observing individual to repeat the observed gesture, there ought to be a good motor matching between the observed action and the one to be repeated. The infants studied by Meltzoff and Moore protrude their tongue in the same direction as the experimenter does (25). The same is true for other instances of resonance behavior of the first type. In contrast, in F5 action generalization characterizes the visual responses of most neurons. Neurons respond regardless of whether the hand that grasps food is seen moving toward the monkey or away to it, of whether the movement is made from above the object or from below. In some neurons even grasping with the mouth is effective.

From a motor point of view all these movements are different, but in terms of meaning they all represent the same action, "grasping".

Third, in many neurons the congruence between the effective observed action and the effective executed action is broad. A neuron that discharges during a specific hand action made by the monkey, e.g. a precision grip, fires not only when the monkey observes the experimenter grasping an object using a precision grip, but also when it observes the experimenter grasping a larger object using ail fingers (11). Neurons with these properties hardly could bc the basis for imitation behavior.

On the basis of these considerations we suggested that F5 mirror neurons are involved not in "imitation" but in action understanding (11, 34). The logic is the following. An individual that emits a movement typically "knows" (predicts) its consequences. This knowledge probably results from an association between the representation of the motor action, coded in F5 and in other motor centers, and the consequences of the action. The "resonance" mechanism in F5 does not determine the appearance of a motor response, but evokes a neural activity that corresponds to that which, when internally generated, represents a certain action. The meaning of an action can be therefore recognized, because of the similarity between the two representations.

This interpretation implies that, unlike the resonance activity of the first type the purpose of which is to determine overt movements, the purpose of the "resonance" in the mirror system is to generate a representation of the goal of an action. The properties of F5, or at least of some neurons of F5 (sec above), have precisely these characteristics. Note that the capacity to generate a goal-directed representation of illovement is present not only in F5 mirror neurons, but also in F5 canonical neurons. This indicates an evolution of the monkey motor cortex from a purely executive system. in which sensory input is hooked up directly to the output systems, to a systern in which part of it acts as a buffer storing the possible actions evoked by the external stimuli.

It is important to make it clear that we do not claim that F5 mirror neurons are exclusively involved in a resonance behavior of the second type. It may well be that in monkey the two resonance levels are not anatomically segregated. It could be, for example, that the mirror neurons that we classified as highly congruent, i.e. those that resonate only when the observed action coincide with the emitted one, underlie resonance activity of the first type, while those broadly tuned are responsible for action comprchension. Alternatively, il may bc that motor areas differeni from F5 are responsible for resonance activity of the first type. Finally, one cannot exclude that resonance activity of the first type concerns only socially relevant behavior. Since monkeys do not communicate using hands, it is possible that this type of behavior is limited in this species to facial or body movements and therefore does not concern hand movements.

Neural basis of resonance behavior in humans

Evidence coming from transcranial magnetic stimulation (TMS), brain imaging and MEG/EEG recording studies provides neurophysiological evidence that resonance mechanisms exist in humans. Where are they located?

Positron emission tomography (PET) experiments showed that during the observation of grasping movements there is an activation of the left superior temporal sulcus (STS), the left rostral part of the inferior parietal lobule (area 40), and the left inferior frontal cortex (area 45) plus the left opercular parietal region and the rostral part of the supplementary motor area (SMA-proper) (14, 35). The first three regions most likely correspond to the monkey cortical areas where neurons were recorded that discharge when the monkey observes biological actions, namely the STS region (4, 30), area 7b (9), and area F5. In area 7b as in F5 there are neurons with mirror properties (9). Finally, there are some preliminary indications thal mirror neurons are present also in the

opercular part of the parietal lobe (our unpublished observations), while no data are available for the SMA.

Logically, the observation of a goal directed action, such as grasping, should activate mirror neurons coding the action goal as well as neurons responsible for resonance behavior of the first type. In the PET experiments on grasping observation, the instructions given the subjects ("observe whether the grasping is donc properly") emphasized essentially the comprehension of the observed action. Thus, the activation of regions involved in the latter behavior could have remained under threshold of statistical significance.

An interesting attempt to differentiate cortical areas related to action understanding and action imitation was made by Decety et al. (6). In a PET experiment they presented subjects with a series of video-taped meaningful and meaningless actions. In one condition the subjects were required to observe them in order to recognize the presented action, in another to observe them in order to repeat the action later on. Unfortunately no control condition was run. As a consequence only those sites were identified that were differentially activated among conditions and not those that were active during a specific condition. In spite of this, two important observations emerge from this study: a) Meaningful actions activated the Broca's area more than meaningless action. This finding on one side replicates the data of previous PET "grasping" experiments (14, 35), on the other demonstrates that the action meaning is important to activate optimally the Broca's area, b) When subjects were instructed to imitate the seen actions there were activation foci in the prefrontal cortex not observed during the recognizing condition. This finding probably has to be related to the role of prefrontal lobe in long term action programming.

Given the experimental difficulty of disentangling different resonance behaviors (e.g. imitation of meaningful actions, obviously, involves their comprehension), the problem of whether there are areas selectively responsible for resonance behavior of the first type is non solved. In favor of the existence of areas of this type (or al least of neuronal systems mediating this behavior) are, however, data coming from TMS and MEG/EEG experiments. As previously mentioned TMS experiments (8) showed thal the cortical excitability increases both when a subject observes meaningful actions (grasping an object) and meaningless actions (simple intransitive arm movements). Furthermore, during observation of a given action the increase of motor evoked potentials were found in those muscles that the subjects use to perform the observed action. This last observation is more in accord with a resonance behavior of the first type rather than with a resonance behavior related to an abstract action recognition.

Direct evidence that cortical motor areas are excited in humans during action observation comes from MEG experiments. Hari et al. (16) recorded neuromagnetic oscillatory activity of the human precentral cortex from healthy volunteers while (i) they were at rest, (ii) they were manipulating a small object, and (iii) they were observing another individual performing the same task. The left and right median nerves were stimulated alternately al intensities exceeding motor threshold and the post-stimulus rebound of the rolandic 15-25 Hz activity was measured. In agreement with previous observations (38), the rebound was strongly suppressed during object manipulation. Most interestingly the rebound was also significantly diminished during action observation. Control experiments confirmed the specificity of the suppression effect. Because the recorded 15-25 Hz activity originales mainly in the precentral motor cortex, it appears that the human primary motor cortex is facilitated during observation of object manipulation as well as during execution of motor tasks. Similar results were obtained also by Cochin et al. (5).

These data might suggest that mirror type activity is present in area 4. This is, however, rather unlikely. First, the primary motor cortex of primates does not recieve visual input. Second, recordings from area FI (area 4) in the monkey did not reveal mirror activity (11). Third, the data of

Cochin et al. (5), although preliminary, indicate an activation also of the premotor areas. It is more plausible, therefore, that the desynchronization of the intrinsic cortical rhythms during action observation in primary motor cortex is due to inputs coming from premotor areas where, given their parietal input, more likely the mirror phenomenon may occur.

How can the TMS and MEG data on one side and PET data on the other be reconciled? Our view is that the activation of area 45 reflects essentially a resonance behavior of the second type. There is no convincing evidence, however, up to now, of an activation of' this area during a motor action. Thus, a direct proof of a resonance phenomenon in area 45 is lacking. It must be noted, however, that during active object grasping, no activation was either observed in area 44, the human homologue of' F5 (2. 31. 32).

The lack of activation of inferior frontal areas in humans during hand-object interactions may be due to specics differences between humans and monkeys. Alternatively, it may be that the experimental tasks used tostudy these areas were inadequate for producing an activation sufficient to be detected by brain imaging studies (15).

Although some previous studies already pointed in this direction (20, 29, 39, 41), a convincing demonstration that hand movements are represented in Broca's area has been only recently given by Binkofski et al. (1). These authors used functional MRI (fMRI) to assess cerebral activation during manipulation of various complex meaningless objects as compared to manipulation of a single simple object. In contrast with previous experiments, where there were discrete movements interrupted by long pauses, the task Binkofski et al. ernployed required continuous finger movements and a constant change in their configurations. The results showed that during manipulation of complex objects there was an activation of area 44, a region in the intraparietal sulcus, area SII and a sector of superior parietal lobule. If one considers that in the monkey the grasping circuit is formed by area AIP, F5 and SII (19, 22, 36) the homology between the human and monkey grasping circuit appears to be very close.

Summing up, there are two firm conclusions that one can draw from the available evidence in humans. First, the observation of hand actions made by others determines an activation of motor/premotor areas. Second. the observation of meaningful actions determines the activation of Broca's area.

How can these findings relate to the two types of resonance phenomena? One possibility is that the resonance phenomena of the two types are mediated by different areas and centers. According to this hypothesis, resonance phenomena of the first type would originate in premotor areas and in the inferior parietal lobe where many neurons discharge in association with skeletal movements. (Mirror neurons have been recently described in the parietal lobe by Fogassi et al. (9). Resonance phenomena of the second type would be mediated by higher premotor areas such as Broca's area.

Alternatively, one can think that the neurons mediating both types of resonance phenomena rather than being segregated in different cortical areas, are present and intermixed in the same areas. The organization of hand movement in F5 (sec above) indicates that some neurons code the goal of an action (c.g. grasping) while others discharge in association with specific movements (e.g. hand closure). A similar organization could be postulated for the resonance behavior. Neurons responding to the observation of simple movements could be intermixed with neurons that repond to the action goal. This mixed organization does not preclude, of course, the possibility that neurons which resonate in response to movements are more concentrated in certain cortical areas, while those that resonate in response to the goal of the actions are mostly concentrated in another one.

In conclusion, the distinction between two types of' resonance phenomena, that we only sketched here, seems to us an important theoretical step for a better understanding of a

mechanism that, although evolutionary very ancient, has by no means lost its importance in the most evolved species. On the contrary, as argued elsewhere (12, 32), our view is that the resonance mechanism represents the extremely interesting case of a basic mechanisin, originally developed for synchronizing the behavior of groups of individuals, which then evolved to form a complex mechanism at the basis of language and, more generally, of interpersonal relations. The challenge now is to solve experimentally the issue of the different types of resonance mechanisms. The joint use of' single neuron recordings and techniques such as fMRI, MEG/EEG and PET should render this task possible.

Summary

This article is subdivided into two parts. In the first part we review the properties of a particular class of premotor neurons, the "mirror" neurons. With this term we define neurons that discharge both when the monkey makes a particular action and when it observes another individual (monkey or human) making a similar action. The second part is an attempt to give a neurophysiological account of the mechanisms underlying behaviors where an individual reproduces, overtly or internally, movenients or actions made by another individual. We will refer to these behaviors as "resonance behaviors". We distinguish two types of resonance behavior. The first type is characterized by imitation, immediate or with delay, of movements made by other individuals. Examples of resonance behavior of this type are the "imitative" beliaviors observed in birds, young infants and patients with frontal lesions. The second type of resonance behavior is characterized by the occurrence, at the observation of an action, of a neural pattern, which, when internally generated. determines the making of the observed action. In this type of resonance behavior the observed action is, typically, not repeated (overtly). We argue that resonance beliavior of the second type is at the basis of the understanding of actions made by others. At the end of the article we review evidence of mirror mechanisms in humans and discuss their anatomical localizations.