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Several neurophysiological studies in monkeys demonstrated that neurons of the agranular frontal cortex code goal-related motor acts, such as reaching an object, grasping it, etc., rather than simple movements. In particular, single neurons of ventral premotor area F5 (Figure 1) code the motor goal at an abstract level, discharging when a monkey grasps an object independent of whether this act is performed with the hand, the mouth or even with a tool. This “internal motor knowledge” is then exploited, through reciprocal anatomical connections between parietal and premotor cortex, by the incoming sensory information, constituting a system matching the sensory input onto specific motor representations. This system enables individuals to attribute a “motor meaning” to the sensory input. One of the best examples of this matching process is provided by mirror neurons.

Mirror neurons in the monkey
Mirror neurons, originally described in monkey area F5, are visuomotor neurons discharging both when a monkey performs a hand or mouth goal-directed motor act (e.g. grasping, biting, or manipulating an object) and when it observes the same or a similar act performed by another individual (Figure 2). A sub-class of mirror neurons respond not only during execution and observation of a motor act, but also to the sound of noisy motor acts such as peanut breaking. Although mirror neurons are generally not influenced by many details of the observed motor acts, recently it has been demonstrated that a consistent number of them can be modulated by the visual perspective (egocentric or third person view) from which a motor act is observed or by the distance at which the observed act is performed. Thus these neurons, beyond encoding the goal of the observed motor acts, can also contribute to recognize some details of it, probably through feedback connections between ventral premotor cortex and posterior, high order visual areas.

The idea that mirror neurons have a crucial role in the understanding of motor acts has been supported by further neurophysiological investigations. In one of these it has been demonstrated that mirror neurons discharge also when the hand-target interaction is hidden behind a screen, thus showing that the motor representation of the observed motor act is retrieved even in absence of its full visual description.

The presence of mirror neurons has been demonstrated also in the inferior parietal cortex, in a cytoarchitectonic area (PFG) strictly linked with the F5 “mirror” sector. Thus, these two areas, together with STS (containing visual neurons responding to the
observation of biological motion,\textsuperscript{7} constitute the functional circuit involved in transforming the visual description of a motor act in its motor representation (see Figure 1).

The mirror system in humans

Several electrophysiological and neuroimaging studies demonstrated the presence of a mirror system also in humans.\textsuperscript{3} TMS stimulation of the motor cortex of subjects observing a grasping motor act elicits a specific enhancement of motor evoked potentials (MEPs) of the same muscles used to execute the same observed motor act. PET and fMRI studies demonstrated that observation of motor acts activates three main areas, likely homologous of the monkey areas activated in the same task, namely STS, supramarginal gyrus and the posterior sector of the inferior frontal gyrus (IFG), plus the anterior intraparietal area (AIP) and, in some cases, the superior parietal lobule.\textsuperscript{1,11} Interestingly, observation of goal-related motor acts performed with different effectors (i.e., mouth, hand and leg) determines a somatotopic activation, with some degree of overlap, of frontal and parietal cortices,\textsuperscript{1} indicating that observation of a motor act performed with a specific effector activates the corresponding motor representation.

More recent studies demonstrated that in humans, like in monkeys, the mirror system can be activated during observation of motor acts performed with a non-biological effector, such as different types of tools and/or a robot arm.\textsuperscript{12} However, by comparing human and monkey brain activation during tool action observation, Peeters and coworkers\textsuperscript{7} showed that only in humans is there an area of the supramarginal gyrus exclusively activated by tool observation.

Intention understanding

A series of experiments in monkeys investigated P5 and PFG neuronal activity while monkeys executed or observed different actions (eating or placing) containing the same motor act (grasping).\textsuperscript{7,8} The results showed that a high percentage of both purely motor and mirror neurons in both areas discharged differentially during both execution and observation of the grasping act, depending on the final goal of the action in which the act was embedded. Thus, the modulation of grasping neurons reflects the action goal, that is the motor intention of the agent involved.

Furthermore, when monkeys had to perform more complex actions the activity of grasping neurons was modulated since its early phases, suggesting that this activity could depend from a neural mechanism, probably located in the prefrontal cortex, that allows one to select actions on the basis of the context.

A mechanism similar to that described in monkeys might play a role in understanding others’ intentions also in humans. An fMRI study by Iacoboni and coworkers\textsuperscript{9} showed that when the context in which a motor act was observed suggested to observing subjects the intention underlying it, there was a differential activation of the right IFG compared with control conditions in which only the context or only the motor act were shown.

Altogether, monkey and human studies indicate that the parieto-frontal mirror network subserves the automatic understanding of motor intentions underlying the actions of others, through a process of retrieval of action representations. It is possible, however, that in cases in which the interpretation of others’ behavior requires reasoning, beyond the ‘mirror’ network other cortical areas, considered to be part of a ‘mentalistic network,’\textsuperscript{12} are involved.

Plasticity of the mirror system

The presence of mirror neurons responding also to tool actions\textsuperscript{10} strongly suggests a plasticity of the mirror system. Examples of this plasticity have been reported also in humans. For instance, Cross et al\textsuperscript{12} demonstrated that the ventral premotor (PMv) and inferior parietal (IPL) activity of expert dancers can be modulated during the observation of new complex whole-body dance sequences only if they are rehearsed.

In an fMRI study, Gazzola and coworkers\textsuperscript{13} found that the observation of hand motor acts in aplasic subjects (born without arms or hands), produced an activation of the mirror system that, in the frontal cortex, included the mouth and foot representations. This suggests a recruitment of cortical representations involved in the execution of motor acts that achieve similar goals using different effectors.

In another fMRI study, Ricciardi and coworkers\textsuperscript{14} showed that in congenitally blind patients listening to the sound of actions there was an activation of the mirror system, as in the normally sighted controls observing and listening to the same actions.

The reorganisation of the motor representa-
tions shown by these studies prompts the possibility to exploit this plasticity for rehabilitative purposes. For instance, Ertelt and coworkers\textsuperscript{15} employed a three weeks action observation therapy on stroke patients with mild paretic hand. A group of them, who had to observe and reproduce motor acts of increasing complexity, showed a motor improvement (evaluated with functional scales), when compared to the control group observing videos showing non-relevant material, and then performing the same motor acts as the first group. Moreover, an fMRI study on the investigated patients showed that during execution of an object manipulation task, the first group, after the therapy, presented a greater activation of areas belonging to the mirror network than the second group.

In agreement with these findings, a recent pilot study based on Virtual Reality Neurorehabilitation\textsuperscript{16} proved that acute stroke patients had particular benefits, as compared to control patients, on recovery of proximal movements and on the ability to perform functional daily life activities after adding, to a standard rehabilitation, exercises (Rehabilitation Gaming System) requiring the execution and observation (through virtual reality) of motor acts such as hitting, grasping or placing a spherical object.

Conclusions

The discovery of the mirror system prompted its investigation in many social cognitive functions in healthy and pathological subjects. One example is represented by the autistic spectrum disorder characterised by a deficit in intersubjective relations, in which a decrease in the function of the mirror circuit has been proposed. Interestingly, EMG and behavioural studies showed that autistic children lack the typical fluidity that characterises the organisation of intentional actions and they are not able to understand intentions when they can rely only on pragmatic information.\textsuperscript{17}