NEUROTOPICS

Original article

Mirror neurons and the predictive mind

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SUMMARY: *Our brain is not only a reactive organ, capable of reacting quickly to the stimuli that arrive from the external environment, but also, and above all, it is a pro-active organ that allows us to make hypotheses, anticipate the consequences of actions, and formulate expectations, thereby enabling us to wrong-foot an adversary. Without this ability, humans would not be able to interact with each other, nor create forms of social coexistence. Certainly evolution has spurred the higher cognitive functions to develop mechanisms of reorganizing action according to unforeseen events as quickly as possible, integrating them into a perception-action cycle that may only take fractions of a second. Recent neuroscientific advances have shown the fallacy of imagining an anatomical and functional dichotomy between perception and action. The discovery of mirror neurons has shown that there is, instead, a very close link between perception and movement, confirming the existence of a relationship between what we perceive and how we act that hinges on the activation of the same neural substrate in both cases. In light of this evidence, perception becomes the ability to interpret an object in terms of the potential movements and actions that the perceiver could activate in relation to it. Motor acts are formulated and anticipated through the joint activity of perception and action and a mechanism of embodied simulation, which automatically perceives "the other" as an agent like oneself whose actions can be predicted on the basis both of their similarity to one's own motor repertoire and the physical characteristics of the situation in question.*

KEY WORDS: *Anticipation, Embodied action, Mirror neurons, Perception.*

INTRODUCTION

The idea that perception involves not just the interpretation of sensorial messages but, first and foremost, an anticipation of the relevant action is hardly new. In 1852 Lotze[7] pointed out the close relationship between perception and action when he argued that the organization of sensorial data is the outcome of its integration with information gleaned from the muscles. Similarly, van Helmholtz (1962)[17] attributed motor control with the ability to match sensations with forecasts based on the motor command itself. In France, Janet (1935)[6] highlighted the predictive nature of perception - an action (possibly restrained) that adapts not merely to the stimulus that provoked it but also to all the other potential stimuli generated by the action itself. "This adaptation to a set of purely possible future stimuli characterises perceptive modes of behaviour" (Janet, 1935, page 31)[6]. To clarify this concept, Janet used the example of an armchair. When we simply look at an armchair, we do not think we are performing an action, but actually this is an illusion: "we have the characteristic action of an armchair already inside us, what we have called a perceptive schema, which in this case is the act of sitting down in a certain fashion in this arm-

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LIST OF ACRONYMS AND ABBREVIATIONS: **GMP** = Generalized Motor Programme.

chair" (Janet, 1935, page 43)[6]. Just like a biological simulator, our brain draws on memory and formulates hypotheses for movement, predisposing the action best suited to the situation, prior to making any movement. Bernstein (1967)[1], one of the fathers of modern physiology, claimed that planning a motor act, in whatever way it is codified by the nervous system, necessarily implies recognition of situations which are bound to happen but do not yet exist[18].

The lengthy evolutionary process of the human species has generated a variety of adaptive biological mechanisms: the architecture of the skeleton, the subtle properties of sensorial receptors, and the formidable complexity of the central nervous system. These mechanisms have solicited our brain to formulate interior models of the body and the world around us that reflect the over-arching laws of nature and permit the survival of each and every animal[8,9]. Bernstein was one of the first investigators who tried to go beyond the traditional description of motor regulation and coordination as a linear succession of four phases: prediction, preparation, execution and verification. He proposed a model based on the action- perception cycle in which the fundamental element is a discriminator that establishes the so-called "required value". This value has three important functions:

1) it identifies the gap between a movement as predicted and as executed, providing a correlation between the two;
2) it enables the recognition of a completed act, making it possible to go on to the next act in a motor sequence;
3) it performs an adaptive function: confronted with something unforeseen, corrective impulses are triggered to re-establish the initial plan of action.

The higher cognitive functions have certainly evolved to develop this ability to reorganize action according to unforeseen events in the fastest possible way in order to give the organism in question a competitive advantage and therefore a better chance of survival. In this way, new events are integrated into the perception-action cycle in only fractions of a second. Hence there must be existing formulae and traces of the movements and actions that have been acquired over time in the central nervous system. Indeed, the existence of such schemata is demonstrated by the fact that we can rely on habitual actions and automatic movements[1].

□ MIRROR NEURONS AND ANTICIPATED ACTION

The traditional idea that perception and action are two distinct processes from a neurophysiological point of view, in which perception is the product of 'associative', primarily temporo-parietal, areas while the control of movement relies on motor and pre-motor areas localised in the rear part of the frontal lobe, has been called into question by some recent findings. In particular the discovery of mirror neurons[4,13] has made it necessary to redefine this relationship, highlighting the dimension involved in human cognition. A number of experiments carried out on both monkeys and humans have shown that the mirror neurons - located in the pre-motor and rear parietal cortex - are activated both when we perform an action and when we see that action performed by others[5]. In other words, the observation of another's action appears to generate a sort of internal simulation of that action through a mechanism that is subconscious, automatic and pre-linguistic. In fact, the activity of the mirror neurons indicates that the motor response is already present in the perception phase: we are no longer dealing with a sequential process, as was traditionally thought, but with a sensorimotor cycle in which the action is not the final outcome of the perceptive process but already an integral part of it. Thus, the ability to predict our own actions or those of others depends on the existence of a system of motor mediation for perception itself[12] that can be considered a form of perceptive simulation of movement. In this sense, predicting the meaning of others' actions does not necessarily involve recourse to forms of inference or reasoning. Rather, it is based on an immediate combination of perception and action. This also disposes of the presumed difference between action as something "active" and perception as something "passive": the latter would in fact contain a sort of embodied intentionality capable of guiding the action towards specific goals. In practice, without the information provided by perception, motor acts would lead nowhere.

According to Berthoz[2], the presence of mirror neurons confirms the existence of a repertoire of pre-perceptions through which the brain is able to simulate actions, foresee their consequences and choose the most appropriate course. In the light of this, perception cannot be viewed as the mere interpretation of sensorial messages; rather, it involves an internal simulation and anticipation of the consequences of an action. Think, for example, of champion skiers. They do not stop at monitoring, and, if need be, correcting the trajectory of their descent on the basis of the information supplied by their sensory organs. They go over the route mentally, anticipating the various stages and imagining possible responses even before an error occurs. Only occasionally does the brain compare the incoming data from the sensorial receptors with the predictions made previously. A discrepancy between the two will cause the skier to make corrections and modify the angle of the knees, speed, etc.[2]. The same goes for other sports. Without this ability to anticipate, tennis players would systematically miss the ball, since hundreds of milliseconds are bound to elapse between synchronizing the muscles needed to take up a correct posture for reception and the moment at which the racquet attains the right inclination, during which the ball will have travelled several metres. This, in fact, is exactly how beginners tend to behave, showing why it is necessary to establish the direction of the ball and its trajectory in advance. In other words, during an action the brain appears to activate two parallel processes: one conservative and the other projective[2]. In the first, which is the more primitive, the brain behaves as a controller, trying to maintain certain variables within the limits defined by the intended action. It deploys gestures, mostly primitive ones, whose characteristics are already codified in specialised neuron groups present in the brain (basal ganglia, motor and pre-motor cortex, cerebellum, etc.). The potential errors involve mechanical quantities such as speed, force etc. The second, projective process has evolved more recently, and uses internal "maps" to simulate a movement without performing it. Through simulation, this process makes it possible to predict the consequences of potential actions and "choose" the best one for the situation[3].

☐ MEMORIES, AIMS AND PLANS AS EMBODIED ACTION

In order to act successfully, one has to be able to remember. Memory is a set of sensorial and motor schemata and habits serving as a system able to recall corporeal perceptions; in a nutshell, it can be called *embodied action*. Procedural memory conserves, albeit at the level of potential, the possibility of actions that have not yet been implemented. Thanks to the perceptive traces of events already experienced and deposited in the memory, we are able to anticipate the future, preparing the appropriate actions to achieve a certain goal.

All the evidence suggests the importance of a proactive physiology that engages in a more lively and direct manner with the surrounding environment than that foreseen by the traditional reactive view of physiology. There is now widespread consensus that perception is generated by different reference systems suited to the actions in progress. In fact, while the receptors measure 'derivatives', the brain mobilises a repertoire of prototypes of shapes, faces, objects and even synergies of movements. The evolution of the brain has produced laws that tend to simplify the geometric, kinetic and dynamic properties of natural movements. But perception is also predictive, thanks above all to memory, which anticipates the consequences of the future action by matching them against those of a past action.

One of the theories most often used to explain the relationship between perception, action and memory - and, in particular, to relate prediction to the consequences of past action and the record of its consequences - is Schmidt's schema theory (1975)[14]. This is based on two fundamental concepts: the GMP and motor schema. The GMP is a motor pattern deposited in the memory and representative of a class of actions that possess the same general structural characteristics (invariants). Among these we can identify:

a) the sequence of muscular contractions involved in a gesture;
b) the temporal structure, meaning the proportion of time used to carry out each single segment of a movement, which remains constant even if the total time of the movement changes;
c) the relative force, meaning the constant proportion between the forces expressed by the various muscles that participate in the action, independent of the degree of overall force.

During the action, the generalized motor programme can undergo variation and be adjusted to adapt to the various situational requirements. This is made possible by the alteration of certain parameters such as the selection of specific muscles or the force and duration of the movement. In fact, one particular movement repeated over and over again will never be identical, particularly in the world of sport, even if its fundamental structure remains unchanged, thereby confirming the existence of a generalized motor programme. Such variations are possible thanks to the motor schemata that represent a generalization of concepts and relationships between concepts deriving from experience. This makes it possible to identify the specific requirements for putting into effect a particular version of a motor programme(11). In other words, if on the one hand the generalized motor programme provides the invariants in the desired gesture, the motor schema selects the specific parameters of the motor response to adapt them to the situational requisites. This schema becomes all the more precise the greater the variations in the parameters applied to the same motor programme. Let us imagine, for example, that as he steps up to take a penalty kick a footballer processes the environmental information and selects the motor programme he considers most appropriate. He will know how to adapt the generalized motor programme to the specific situation, modifying such parameters as timing and extent of movement, foot position, and so on, to meet the specific requisites of the situation(16). The schema becomes increasingly precise as the variability in any one motor programme increases. In fact, with each variation of class, and the increase in accuracy of the feedback, the schema is updated and established as a generally valid rule. At the same time, specific information is eliminated, which solves the problem of having to store an excessive amount of data.

Schmidt(15) distinguishes between two states of memory based on the relationships between the four sources of information, clarifying two aspects of his concept. The schema of *recall* enables a new response, providing the generalized motor programme with the necessary parameters for carrying out the movement and adapting it to the requisites of the task in hand. While the schema of *recognition* enables evaluation of the level of appropriateness of the movement undertaken, comparing the incoming sensory feedback with what was foreseen and making any necessary corrections. This makes it possible to anticipate the sensory consequences of the response and compare them, both during and after the movement, with the incoming feedback. In this way information about the result is obtained, and any deviation between the expected and actual sensorial consequences is recognised as an error.

A very similar concept was formulated by Neisser(10), who considers perception as a 'cycle' in which the fundamental structures are anticipatory schemata, meaning programmes of action that prepare the subject to acquire certain information that will, in turn, modify the original schema. In light of these considerations, it no longer seems plausible to subordinate the motor functions to the "higher" mental activities, as if the body were inferior to the mind. Indeed, even though they form part of different systems, perception and action are two closely integrated functions. In terms of evolution, both have contributed to selecting motor schemata and predictive capacities that we still use today, millions of years on, to adapt to the environment around us.

☐ CONCLUSIONS

The experimental data that has been acquired over recent decades has shown that the classic dichotomy between 'the brain that knows' and 'the brain that acts', i.e., between perceptive processes and motor functions, is now hard to endorse or apply, except for purely analytical purposes. The phylogenetic development of the higher-order areas can no longer be viewed as a mere reinforcement of the processing systems that intervene between sensory input, on the one hand, and motor output, on the other. One of the fundamental prerequisites for the development of the cognitive capabilities in the brains of primates was precisely the combined action of cognitive processes and motor functions. In view of these factors it seems plausible that the central nervous system has undergone not only a quantitative evolution, but also a qualitative one. If this hypothesis proves to be grounded in fact, then the anatomical connections and functional characteristics of the cortical regions that are typically considered associative, perceptive or motoric could, instead, account for the emergence of cognitive, perceptive and motor skills from the functional integration of information that can only be traced back to the individual domains in theoretical terms.

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