Mirror neurons: Enigma of the metaphysical modular brain

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Abstract

Mirror neurons are one of the most important discoveries in the last decade of neuroscience. These are a variety of visuospatial neurons which indicate fundamentally about human social interaction. Essentially, mirror neurons respond to actions that we observe in others. The interesting part is that mirror neurons fire in the same way when we actually recreate that action ourselves. Apart from imitation, they are responsible for myriad of other sophisticated human behavior and thought processes. Defects in the mirror neuron system are being linked to disorders like autism. This review is a brief introduction to the neurons that shaped our civilization.

Key words: Autism, neurons, visuospatial

INTRODUCTION

Mirror neurons represent a distinctive class of neurons that discharge both when an individual executes a motor act and when he observes another individual performing the same or a similar motor act. These neurons were first discovered in monkey's brain. In humans, brain activity consistent with that of mirror neurons has been found in the premotor cortex, the supplementary motor area, the primary somatosensory cortex, and the inferior parietal cortex [Figure 1].

Originally discovered in a subdivision of the monkey's premotor cortex, area F5, mirror neurons have later been also found in the inferior parietal lobule (IPL).[1] IPL receives a strong input from the cortex of the superior temporal sulcus (STS), a region known to code biological motion, and sends output to ventral premotor cortex including area F5.[2]

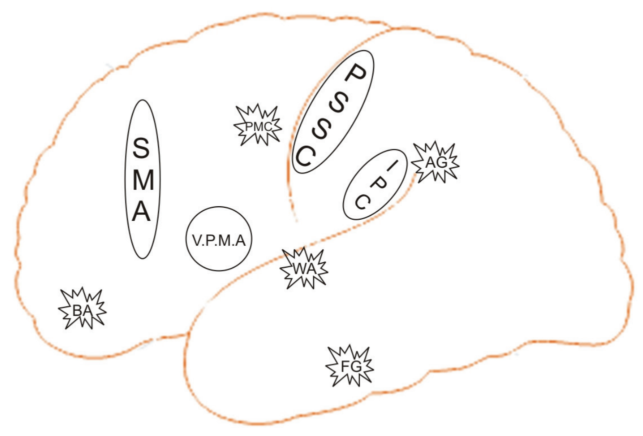

Figure 1: The mirror neuron system in the human brain. (1) SMA: Supplementary motor area, (2) PSSC: Primary somato sensory cortex, (3) IPC: Inferior parietal cortex, (4) VPMA: Ventral premortal area, neurons having mirror properties, BA: Broca's area, WA: Wernicke's area, FG: Fusiform Gyrus, AG: Angular gyrus, PMC: Primary motor cortex

Neurophysiological (EEG, MEG, and TMS), and brain-imaging (PET and fMRI) experiments provided strong evidence that a fronto-parietal circuit with properties similar to the monkey's mirror neuron system is also present in humans.[3] As in the monkey, the mirror neuron system is constituted of IPL and a frontal lobe sector formed by the ventral premotor cortex plus the posterior part of the inferior frontal gyrus (IFG).

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DEVELOPMENT

Human infant data using eye-tracking measures suggest that the mirror neuron system develops before 12 months of age, and that this system may help human infants understand other people's actions. Two closely related models postulate that mirror neurons are trained through Hebbian or associative learning.[4,5]

THE HEBBIAN THEORY

Donald Hebb in 1949 postulated that a basic mechanism for synaptic plasticity wherein an increase in synaptic efficacy arises from the presynaptic cell's repeated and persistent stimulation of the postsynaptic cell. When an axon of cell A is near enough to excite a cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased. The theory is often summarized as "Cells that fire together, wire together." This Hebbian theory attempts to explain "associative learning", in which simultaneous activation of cells leads to pronounced increases in synaptic strength between those cells. Such learning is known as Hebbian learning.

DISCOVERY

In 1990s, a group of neurophysiologists placed electrodes in the ventral premotor cortex of the macaque monkey to study neurons specialized for the control of hand and mouth actions.[6] They recorded electrical signals from a group of neurons in the monkey's brain while the monkey was allowed to reach for pieces of food, so the researchers could measure their response to certain movements. They found that some of the neurons they recorded from would respond when the monkey saw a person pick up a piece of food as well as when the monkey picked up the food.

In another experiment, they showed the role of the mirror neuron system in action recognition, and proposed that the human Broca's region was the homologue region of the monkey ventral premotor cortex. Subsequently, a study by Ferrari Pier Francesco and colleagues described the presence of mirror neurons responding to mouth actions and facial gestures.[7]

A recent experiment by Christian Keysers and colleagues have shown that, in both humans and monkeys, the mirror system also responds to the sound of actions.[8] Functional magnetic resonance imaging (fMRI) can examine the entire brain at once and suggests that a much wider network of brain areas shows mirror properties in humans than previously thought. These additional areas include the somatosensory cortex and are thought to make the observer feel what it feels like to move in the observed way.[9] Neuropsychological studies looking at lesion areas that cause action knowledge, pantomime interpretation, and biological motion perception deficits have pointed to a causal link between the integrity of the IFG and these behaviors.[10,11] Transcranial magnetic stimulation studies have confirmed this as well.[12]

Mukamel *et al.* recorded activity from 1177 brain neurons of 21 patients suffering from intractable epilepsy. The patients had been implanted with intracranial depth electrodes to identify seizure foci for potential surgical treatment. Electrode location was based solely on clinical criteria; the researchers, used the same electrodes to "piggyback" their research. The experiment included three phases; making the patients observe facial expressions (observation phase), grasping (activity phase), and a control experiment (control phase). In the observation phase, the patients observed various actions presented on a laptop computer. In the activity phase, the subjects were asked to perform an action based on a visually presented word. In the control task, the same words were presented, and the patients were instructed not to execute the action. The researchers found a small number of neurons that fired or showed their greatest activity both when the individual performed a task and when they observed a task. Other neurons had anti-mirror properties, that is, they responded when the participant saw an action but were inhibited when the participant performed that action. The mirror neurons found were located in the supplementary motor area and medial temporal cortex.[13]

POSTULATED FUNCTIONS OF MIRROR NEURONS IN HUMANS

Intention understanding

Mirror neurons are associated with one of the most intriguing aspect of our complex thought process, that is "Intention understanding". There are two distinct processes of information that one can get observing an action done by another individual. The first component is WHAT action is being done? And the second more complex component is WHAT FOR or, WHY (Intention) the action is being done. Figure 2 is a representation of the consequences described. The complex beauty of the discussed subject is the second component where our mirror neurons premonate the future action which is yet to occur. Two neuroscientists[14] first hypothesized that mirror neurons are involved in intention understanding, which was later supported by fMRI study. In this experiment, volunteers were presented with hand actions without a context and hand actions executed in contexts that allowed them to understand the intention of the action agent. The study demonstrated that actions embedded in contexts yielded selective activation of the mirror neuron system. This indicates that mirror areas, in addition to action understanding, also mediate the understanding of others' intention.[15] These data indicate that the mirror neuron system is involved in intention understanding, though, it fails to explain the specific mechanisms underlying it.

In order to explain this hypothesis, a study[16] was carried out on two rhesus macaque monkeys [Figure 3]. The monkeys were trained to perform two actions with different goals. The schematic representation is shown in Figure 2.

In the first, the monkey had to grasp an object in order to place it in a container. In the second, it had to grasp a piece of food to eat it. The initial motor acts, reaching and grasping, were identical in the two situations, but the final goal oriented action was different. The activity of neurons was recorded from the IPL, which has long been recognized as an association cortex that integrates sensory information. The results showed that 41 mirror neurons fired selectively when the monkey executed a given motor act (e.g. grasping). However interestingly, only specific sets (15 neurons) within the IPL fired during the second goal constrained acts.

Some of these "action-constrained" motor neurons had mirror properties and selectively discharged during the observation of motor acts when these were embedded in a given action (e.g., grasping-for-eating, but not grasping-for-placing). Thus, the activation of IPL action-constrained mirror neurons give information not only about, but also on why grasping is done (grasping-for-eating or grasping-for placing). This specificity allowed the observer not only to recognize the observed motor act, but also to code what will be the next motor act of the not-yet-observed action, in other words to understand the intentions of the action's agent.

Autism and intention understanding

It has been postulated and proved by neuroscientists that the inability of autistic children to relate to people and life situations in the ordinary way depends on a lack of a normally functioning mirror neuron system.[17-19] EEG recordings mu waves from motor areas are suppressed when someone watches another person's move, a signal that may relate to the mirror neuron system. This suppression was less in children with autism.

Basically autism is characterized by two neuropsychiatric abnormalities. First is the defect in the social-cognitive domain which presents as mental aloneness, a lack of contact with the external world and lack of empathy. The second is sensorimotor defects like temper tantrums, head banging, and some form of repetitive rituals. All these are now suggested to be because of some anomaly of the mirror neuron development. One interesting phenomena in autism is the inability to comprehend abstract reasoning and metaphors, which in normal humans is subserved by left supramarginal gyrus rich in mirror neurons. Mirror neuron abnormalities have also been blamed for a number of other autistic problems like language difficulties, self-identification, lack of imitation, and finally intention understanding.

However, the autistic enigma continues as whether the primary deficit in intention understanding found in autistic children is due to damage of the mirror neuron system as it is responsible for understanding the actions of others, or rather there exists more basic defects in the organization of the motor chains. In other words, the fundamental deficit in autistic children resides in the incapacity to organize their own intentional motor behavior.

Emotions and empathy

Many studies have independently argued that the mirror neuron system is involved in emotions and empathy.[20-23] Studies have shown that people who are more empathic according to self-report questionnaires have stronger activations both in the mirror system for hand actions and the mirror system for emotions, providing more direct support for the idea that the mirror system is linked to empathy. Functions mediated by mirror neurons depend on the anatomy and physiological properties of the circuit in which these neurons are located. Emotional and empathetic activations were found in parieto-

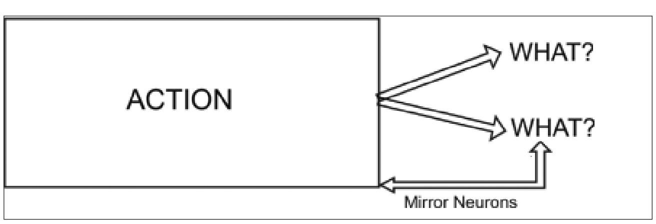

Figure 2: Understanding of "what" and "why" actions through mirror neuron system

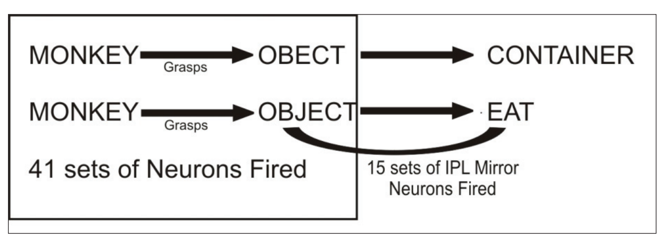

Figure 3: The selective activation of different neurons in different goal oriented tasks

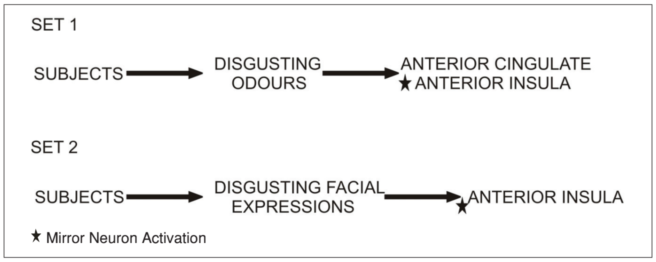

Figure 4: The mirror neurons of the anterior insula fires at a basic emotional theme, irrespective of different modality of portrayal

premotor circuits responsible for motor action control. In a fMRI experiment[24] represented schematically below, [Figure 4] one group of participants were exposed to disgusting odorants and, the other group, to short movie clips showing individuals displaying a facial expression of disgust. It was found that the exposure to disgusting odorants specifically activates the anterior insula and the anterior cingulate. Most interestingly, the observation of the facial expression of disgust activated the same sector of the anterior insula.[25] In agreement with these findings, the data are obtained in another fMRI experiment that showed activation of the anterior insula during the observation and imitation of facial expressions of basic emotions.

Similar results[26,27] have been obtained for felt pain and during the observation of a painful situation, which was involved another person loved by the observer. Taken together, these experiments suggest that feeling emotions is due to the activation of circuits that mediate the corresponding emotional responses.

Evolution of language and mirror neurons

The discovery of mirror neurons provided strong support for the gestural theory of speech etymology. Mirror neurons create a direct link between the sender of a message and its receiver. Thanks to the mirror mechanism, actions done by one individual become messages that are understood by an observer without any cognitive mediation. The observation of an individual grasping an apple is immediately understood because it evokes the same motor representation in the parieto-frontal mirror system of the observer. On the basis of this fundamental property of mirror neurons and the fact that the observation of actions like hand grasping activates the caudal part of IFG (Broca's area), neuroscientists proposed that the mirror mechanism is the basic mechanism from which language evolved.[28]

Humans mostly communicate by sounds. Sound-based languages, however, do not represent the only natural way for communication. Languages based on gestures (signed languages) represent another form of complex, fully-structured communication system. This hypothesis argues that speech is the only natural human communication system, the evolutionary precursor of which is from animal calls. The argument goes as follows: Humans emit sound to communicate, animals emit sounds to communicate, therefore human speech evolved from animal calls.

The contradictions of the above syllogism are:

- The anatomical structures underlying primate calls and human speech are different. Primate calls are mostly mediated by the cingulate cortex and by deep, diencephalic, and brain stem structures. In contrast, the circuits underlying human speech are formed by areas located around the Sylvian fissure, including the posterior part of IFG.
- Animal calls are always linked to emotional behavior contrary to human speech.
- Speech is mostly a dyadic, person-to-person communication system. In contrast, animal calls are typically emitted without a well-identified receiver.
- Human speech is endowed with combinatorial properties that are absent in animal communication.
- Humans do possess a "call" communication system like that of non-human primates and its anatomical location is similar. This system mediates the utterances that humans emit when in particular emotional states (cries, yelling, etc.). These utterances are preserved in patients with global aphasia.

THEORIES OF LANGUAGE EVOLUTION AND ROLE OF MIRROR NEURON SYSTEM

The alternate hypothesis

According to this theory, the initial communicative system in primate precursors of modern humans was based on simple, elementary gesturing.[29] Sounds were then associated with the gestures and became progressively the dominant way of communication. In fact, the mirror mechanism solved, at an initial stage of language evolution, two fundamental communication problems: Parity and direct comprehension. Thanks to the mirror neurons, what counted for the sender of the message also counted for the receiver. No arbitrary symbols were required. The comprehension was inherent in the neural organization of the two individuals.

It is obvious that the mirror mechanism does not explain by itself the enormous complexity of speech. but, it solves one of the fundamental difficulties for understanding language evolution, that is, how and what is valid for the sender of a message become valid also for the receiver. Hypotheses and speculations on the various steps that have led from the monkey mirror system to language have been recently advanced.[30]

In humans, functional MRI studies have reported finding areas homologous to the monkey mirror neuron system in the inferior frontal cortex, close to Broca's area, one of the hypothesized language regions of the brain. This has led to suggestions that human language evolved from a gesture performance/understanding system implemented in mirror neurons. Mirror neurons have been said to have the potential to provide a mechanism for action-understanding, imitation-learning, and the simulation of other people's behavior. It must be noticed that the mirror neuron system seems to be inherently inadequate to play any role in the syntax, given that this definitory property of human languages which is implemented in hierarchical recursive structure is flattened into linear sequences of phonemes making the recursive structure not accessible to sensory detection.

Theory of cross-modal abstraction

The ability to make consistent connections across different senses may have initially evolved in lower primates, but it went on developing in a more sophisticated manner in humans through remapping of mirror neurons which then became co-opted for other kinds of abstraction that humans excel in, like reasoning metaphors. Development of sophisticated modules inside the brain makes us unique as far as language is concerned.

Examples: The connections between the inferior temporal gyrus (fusiform gyrus/visual processing area) and the auditory area guide sound mediated visual abstraction/ synesthesia.

V. S. Ramachandran, a cognitive neuroscientist, demonstrates this through his famous bouba-kiki effect through cross-modal abstraction [Figure 5]. In this experiment, if we are to name the following diagrams with two given options (bouba and kiki) then, our brain predominantly names Figure 1 as bouba, and Figure 2 as kiki.[31]

Analysis of bouba is abstracted in the visual center as somewhat gross, voluptuous, rounded, etc., and kiki is abstracted as somewhat sharp or more chiseled.

Example 2: Similarly doing "pincer-like" hand gestures while pronunciation of terms like "tiny", "little", "diminutive", and pouting the lips outwards while pronunciation of words like " you" meaning pointing towards someone.

These features signify cross-modal connections of neurons between face and hand area in the motor cortex (motor-to-motor synkinesia).

Onomatopoiec theory

This theory also revolves around mirror neurons. Onomatopoeia show how man perceives sound. Sounds are defined as disturbances of mechanical energy that propagates through matter as a wave. What makes a particular sound distinct from others are its properties like frequency, wavelength, period, amplitude, and speed. Onomatopoeia is an attempt to produce the sound we hear by converting it into symbols. For instance, we would say the sound a gun makes when it is fired is "BANG". Although the actual sound is different, we have come to associate "BANG" with a gun. This symbolic association of sound which we perceive through vision in the form of a specific word with correct interpretation is hypothesized to be possible because of mirror neurons.

Theory of recursive em bedding

Michael Corballis, an eminent cognitive neuroscientist, argues that what distinguishes us in the animal kingdom is our capacity for recursion, which is the ability to embed our thoughts within other thoughts. "I think, therefore I am" is an example of recursive thought, because the thinker has inserted himself into his thought. Recursion enables us to

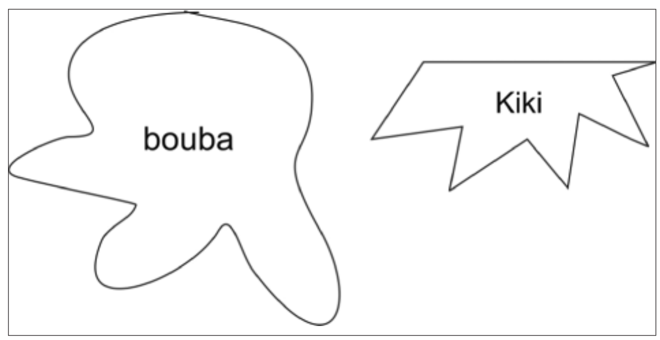

Figure 5: Demonstrates the role of mirror neurons in sound mediated visual abstract reasoning

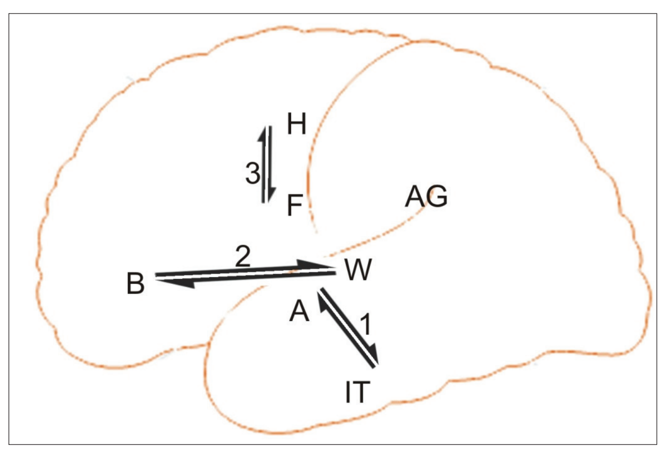

Figure 6: A, auditory cortex (Hearing); B, Broca's area (speech and syntax); W, Wernicke's area (semantics); AG, angular gyrus (cross-modal abstraction); H, hand area; IT, inferior temporal cortex (Fusiform area); F, face area. 1, Bouba–Kiki effect; 2, arcuate fasciculus for cross domain mapping between sound contours and motor maps; 3, cortical motor to motor mapping (synkinesia)

conceive of our own minds and the minds of others. It also gives us the power of mental "time travel" that is the ability to insert past experiences, or imagined future ones, into present consciousness. Corballis demonstrates how these recursive structures led to the emergence of language and speech, which ultimately enabled us to share our thoughts, plan with others, and reshape our environment to better reflect our creative imaginations. Mirror neurons shape the power of recursive embedding.

Theory of mind

This theory suggests that humans can construct a model in their brains of the thoughts and intentions of others. We can predict the thoughts, actions of others. The theory holds that humans anticipate and make sense of the behavior of others by activating mental processes that, if carried into action, would produce similar behavior. This includes intentional behavior as well as the expression of emotions. The theory states that children use their own emotions to predict what others will do. Therefore, we project our own mental states onto others. Mirror neurons are activated both when actions are executed, and the actions are observed. This unique function of mirror neurons may explain how people recognize and understand the states of others; mirroring observed action in the brain as if they conducted the observed action.[32]

A schematic diagram showing the various areas in the brain that may have accelerated the evolution of protolanguage [Figure 6].[33]

Human self-awareness

It has been speculated that mirror neurons may provide the neurological basis of human self-awareness. Mirror neurons can not only help simulate other people's behavior, but can be turned "inward" to create second-order representations or meta-representations of ones own earlier brain processes. This could be the neural basis of introspection, and of the reciprocity of self-awareness and other awareness.[34]

CONCLUSION

Although the enigma of human brain is unfathomable, but still the indefatigable attempts made by the ever aspiring cognitive neuroscientsts has opened up a realm of metaphysical secrets in the mirror neuron modular brain that has shaped our civilization.

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