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Mirrors, Mirrors in the Brain…..

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One of the main functions of social interactions is to perceive and interpret the behaviors of others. This high level process of cognitive deduction appears to be based on the activity of certain cortical neurons that electrically respond to perception-action coupling. This brief review discusses what we currently know about these visual-motor neurons in the context of their phylogeny, ontogeny and cognitive function.

Introduction

In 1992 di Pellegrino et al reported that a subset of neurons in the monkey brain "fired" action potentials not only when the animal performed certain motor tasks but also when the monkey observed others perform the same motor tasks (Fig. 1). In a subsequent publication the same group named the aforementioned nerve cells, mirror neurons, as they electrically respond to both observed and executed actions (Gallese et al., 1996). Ever since their discovery, mirror neurons have been thought of as conduits in providing an internal experience of another individual's action, intention or emotion (Casile et al., 2011). It is also thought that the matching response of such context-specific neurons may underlie the ability to imitate another subject's action, and thereby learn (Oztop et al., 2013).

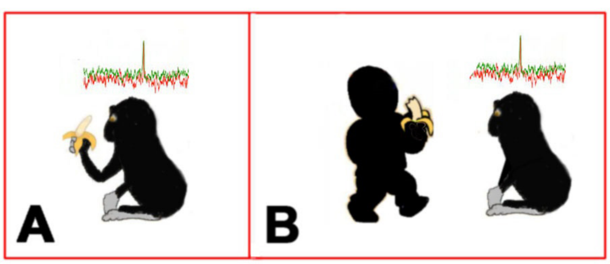

Fig. 1. Mirror neuron responses in a macaque monkey during social interactions with a human. In (A), the monkey grasps a banana to eat it. This specific goal-directed motor act leads to action potential activities within primary motor and parietal cortices. When the monkey observes the same motor act in a human primate (B), mirror neurons discharge as if the monkey was performing the motor act himself. Thus, a clustering of mirror neurons within the cortex responds during the execution as well as the observation of goal-directed motor acts. Mirror neurons therefore link "intention understanding" between two different species.

Given that monkeys and humans are social species, it was predicted that a similar mirror neuron system was present in the human brain as well. Indeed, functional magnetic resonance imaging (fMRI) experiments showed a neural system that strongly responds to the intention component of a behavioral act (Rizzolatti et al., 2006; Kilner and Lemon, 2013). The integration of mirror neurons with their specific connectivity to the level of cognition is intriguing and points to the possibility that social interactions involve a passive and active encoding of information between the observer and the observed, respectively (Acharya and Shukla, 2012). As discussed above, a visual input to the mirror neuron system is apparently required for encoding the actions of others. However, recent experimental results demonstrate the existence of auditory mirror neurons with encoding response properties similar to those of visual-motor neurons (Kohler et al., 2002; Keysers et al., 2010). Thus, several sensory systems might be part, either individually or together, of a neural input that contributes to mirror neuron discharge during action execution and observation (Kilner and Lemon, 2013).

Mirror Neurons in the Brain

A consistent body of evidence shows that mirror neurons are predominantly located within cortical motor areas of the macaque monkey brain, namely premotor, primary motor and parietal cortices of both hemispheres (Gallese et al., 1996; Nelissen et al., 2005; Fogassi et al., 2005; Dushanova and Donoghue, 2010). These neuroanatomical studies strongly suggest that the action potential activity of mirror neurons underlines motor acts, including mouth movements and facial gestures (Ferrari et al., 2003). Because cortical motor neurons are anatomically linked to descending corticospinal tract pathways (e.g., pyramidal tract neurons), the integration of different functional motor circuits (e.g., somatosensory cortex) appears to be critical for the connectivity of mirror neurons to broad motor outcomes.

As stated earlier, neuroanatomical studies of mirror neurons using fMRI have confirmed the presence of a mirror neuron system in human cortical areas that is consistent with those previously identified in monkeys (Molenberghs et al., 2013). More specifically, the core of the human mirror neuron system includes the inferior frontal gyrus and the inferior parietal lobule (Fig. 2). These findings suggest that human brains also use mirror neurons for guiding social interactions, and that cortical layers, columns, microcircuits or cells encoding mirror responses are broadly homologous across different social species.

Phylogeny of Mirror Neurons

The primate brain has undergone a significant level of evolutionary sculpting as exemplify by increased cortical encephalization, hemispheric lateralization and maturational delay (Seeley et al., 2006). At the level of synaptic transmission and neuronal morphology, however, little differentiates humans from other animals. Thus, a mirror neuron system is likely deeply rooted in evolutionary biology. In this context, certain areas of the primate cortex are thought to be ancient in phylogeny, including the anterior cingulate cortex and frontoinsula (von Economo et al., 1926; Sanides, 1969; Seeley et al., 2006). This evi-

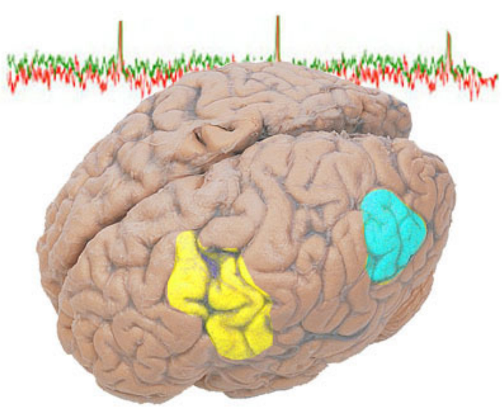

Fig. 2. Mirror neurons within the human brain. The organization pattern of mirror neurons in monkeys has been analyzed with fine-grain anatomical resolution, whereas that of humans has been determined with a spatial resolution of around 5 mm in fMRI studies. Regardless, mirror neurons with action potential profiles similar to those of the monkey brain reside in the inferior frontal gyrus (yellow) and the inferior parietal lobule (blue). Human mirror neurons provide a direct internal experience of another's person's act or intention.

dence highlights the possibility that ancestral mirror neurons might have evolved within the vertebrate lineage to couple relatively simple perception-action patterns of behavior that could have been maximized during the course of animal evolution for tracking one's own behavior, and later for mimicking the actions of others (Fig. 3). Obviously, all of these perception-action patterns of behavior would have been accomplished without a fully-structured communication system (i.e., speech or other sound-based signals).

It should be noted that additional brain circuits appear to be involved in the mirror neuron system. For instance, the basal ganglia and subcortical areas of the brain, including the insula and cingulate cortices also exhibit action potential properties of mirror activity (Wicker et al., 2003; Singer et al., 2004; Alegre et al., 2010). Of interest, the basal ganglia and insula are phylogenetically ancient structures widely shared with other vertebrate brains, including the avian brain. Thus, it is not surprising to find that an audio-vocal mirror system occurs in birds as well (Prather et al., 2008), further supporting the hypothesis of an ancient phylogenetic origin of mirror neurons (Bonini and Ferrari, 2011). This hypothesis also suggests that different social species arrive at similar solutions to cognitive problems not because they are closely related, but because they have experienced similar selection pressures (i.e., evolutionary convergence).

Fig. 3. Presence of mirror neurons and mirror-like mechanisms in vertebrate brains is widespread. The underlying neural mechanisms of cognition are found in humans, monkeys and birds. It is conceivable that many other vertebrate species possess mirror neurons that imitate social acts of behavior. It should be noted that additional social interactions involving a high degree of imitation occur in humans, monkeys, dogs and other vertebrate species. This behavior is a well-documented phenomenon known as contagious yawning. It is not known whether mirror neurons are involved in the reciprocity of contagious yawning among humans. Nevertheless, contagious yawning is another example of a direct and immediate imitation of others' behavior.

Ontogeny of Mirror Neurons

An important issue concerning the evolution of primate mirror neurons is determining when they initially emerge during ontogeny. Although the answer to this query is unknown, a growing body of ultrasonographic evidence suggests that sensorimotor mechanisms of self-recognition, if not innate, develop early in prenatal life (Bonini and Ferrari, 2011). For instance, facial gestures, mouth and hand movements are detected in the intrauterine environment where monkey and human fetuses refine their motor skills (Bonini and Ferrari, 2011). After birth, infant primates have the facial and mouth control to imitate facial expressions and mouth movements of others, particularly those of caregivers (Casile et al., 2011). The early onset of sensorimo-

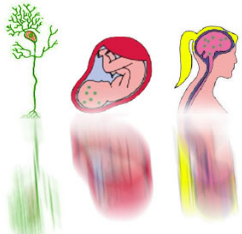

Fig. 4. Schematic diagram depicts the ontogeny of mirror neurons in the primate brain. By comparing human developmental milestones with those of the monkey brain, tantalizing clues about the emergence of mirror neurons are being uncovered. Foremost is the possibility that an automatic recognition system may be operative early in brain development. A functional sensorimotor matching mechanism would subsequently be shaped and pruned by social experiences, particularly those experiences provided by caregivers. Mirror neurons or mirror-like mechanisms may be hard-wired early in fetal development.

tor mechanisms of self-recognition and the spontaneous recognition of others suggest, but do not prove, that a mirror neuron system is cognitively operating in the fetal or neonatal brain to produce action potential patterns indicative of deductive reasoning. Nevertheless, data inferred from brain imaging techniques and electroencephalography in infant primates strongly suggest an early developmental presence of core perception-action coupling systems (Casile et al., 2011). Several anatomical studies further support this idea as myelinization of corticospinal axons in both monkeys and humans have a similar time course of completion, and large bipolar projecting neurons of the anterior cingulate and frontoinsular cortex are immunocytochemically identified late in their brain development (Oliver et al., 1997; ten Donkelaar et al., 2004; Seeley et al., 2006). These pieces of experimental evidence are compatible with the idea that mirror neurons are not only ancient and widespread but also functionally relevant in uterine life (Fig. 4).

Conclusion

Taken together, neural activity of mirror neurons underlies a specific form of understanding others' behavior, and sensorimotor experiences are critical for producing mirror neuron responses.

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Bibliographies

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Editor's Column

Spring is here for most of the country (we hope). It has been a brutal winter for a lot of the country, and as I write this in mid-April, another cold front is descending on the northern states. Here in Florida, we have had a warmer than normal winter, and the weather is beautiful today. The forecasters are predicting a quiet hurricane season this fall, possibly with only three hurricanes, due to a strong El Niño in the Pacific. I hope that they are right.

It seems like only a short time ago that we were attending the last Society for Neuroscience meetings in San Diego. However, we are half way to the next meeting in Washington, DC. I hope that many of you are making plans to attend that meeting. It should be a great time. Also, while you are making your plans, you should think about attending the International Neuroethics Society (INS) meeting on November 13-14 just before the Society for Neuroscience meetings. The INS is an organization of professionals who share an interest in the social, legal, ethical and policy implications of advances in neuroscience.

Due to the tremendous strides that have been made in the area of brain and behavior in recent years, it is becoming increasingly important that we as neuroscientists take an active interest in how our discoveries and information are being used in society. What are the ethical implications for people and society of a better understanding of how the brain functions and what controls our thoughts and actions? It is very important that our students begin to understand the ethics of neuroscience and take them into consideration in planning research. The INS has an active student group and has just announced a Student Essay contest with prizes for the best essays. Perhaps you have a student that would be interested in entering. For more information, please go to www.neuroethicssociety.org.

This issue of the Kopf *Carrier* is another in our Neuroscience Reviews by German Torres, Ph.D. and his colleagues. It is a very informative issue about the fascinating function of mirror neurons in the brain. These strange neurons become active when a human or animal performs an action but also when the individual sees another individual performing that action. They seem related to the sense of empathy with the other individual and to an individual's sense of how other individuals feel and behave. In a context of neuroscience, understanding these very important neural functions has tremendous ethical implications that are only beginning to be understood.

I hope that all our readers have a productive, restful and happy summer (whenever it gets here) and come to fall recharged and productive. If any of you want to write an article for the *Carrier*, please contact me for specifics.

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