Mirror neuron system as the joint from action to language

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Abstract: Mirror neuron system (MNS) represents one of the most important discoveries of cognitive neuroscience in the past decade, and it has been found to involve in multiple aspects of brain functions including action understanding, imitation, language understanding, empathy, action prediction and speech evolution. This manuscript reviewed the function of MNS in action understanding as well as language evolution, and specifically assessed its roles as the bridge from body language to fluent speeches. Then we discussed the speech defects of autism patients due to the disruption of MNS. Finally, given that MNS is plastic in adult brain, we proposed MNS targeted therapy provides an efficient rehabilitation approach for brain damages conditions as well as autism patients.

Keywords: mirror neuron system; action understanding; language; rehabilitation

1 Introduction

Ago Ergo Cogito: “I act, therefore I think”. How do words, songs and characters become meaningful to us? An embodied theory of cognition suggests that meanings consist of all actions we can take under specific circumstances combined with previous experiences that we keep in our minds. This hypothesis was strongly supported by recent works on mirror neuron system (MNS) which functions as the joint from action to language comprehension.

Mirror neuron represents a class of motor neurons that discharge both in action execution and observation of the same action. MNS was firstly discovered in premotor area of monkey, and spikings were recorded from F5 area (part of the premotor cortex that controls action execution) neurons when the monkey observed the hand movements of the investigators or itself performs such an action^[1-3]. This is of particular interest at that time as no previous studies co-located the execution and observation of an action in the same neuron.

Following studies determined a large population of neurons with such a “mirror-like” property, which distributed from F5, through superior temporal sulcus (STS)^[4,5], to area 7b or PF^[2,6] that receives input from STS and sends outputs to the ventral premotor cortex including area F5.

The mirror-mimic property of MNS inside the brain raised a number of questions on its function: does the firing reflect the process of action understanding? How many actions could be understood via individual mirror neurons? What triggered the MNS activity and how it was further processed in connected brain areas? Are there mirror neurons in human beings and other species, and if so, what are their roles in brain evolution and daily cognition? In the following paragraphs, we reviewed the function of MNS in action understanding and language evolution. Specifically, we further assessed the role of MNS as the bridge from body language to speeches, and that disruption of MNS results in speech defects of autism patients. Finally, given that MNS is plastic in adult brains, we discussed the application of MNS based therapy on rehabilitation approaches to autism, brain trauma as well as other disorder diseases.

2 The role of MNS in action understanding

MNS may participate in a variety of brain functions, including action understanding^[7], imitation^[1], language un-

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derstanding^[8], empathy^[9], action prediction^[10] and Speech Evolution^[11]. Among the arsenal of participations, one of the best studied functions of MNS is action understanding, which means the same mirror neuron will go firing when specific actions were performed or observed, including hand movements and other body actions.

How can mirror neurons mediate the understanding of actions performed by others? The proposed mechanism is rather simple: Observed actions automatically induce motor representations in the Mirror Neuron System of observer or the monkey, which transforms visual information into knowledge^[7]. An intriguing question is that whether activated MNS reflects an understanding of result of this action, namely, the intention of action, or the mirror neurons just fire upon specific visual features of observed actions, such as grasping, holding and bringing to the mouth, namely, the action recognition? Umiltà *et al.*^[12] examined the F5 mirror neurons firing in two psychologically distinct contexts to determine this question. In “full vision” condition, the monkey was shown a fully visible action directed toward an object. In the “hidden” condition, the monkey can observe the same action with its final, critical part hidden (shown in training sessions thus the monkey can only “predict” that the target object was present behind the occluder). It is quite interesting that more than half of the recorded neurons in MNS discharged when the monkey observed the partly hidden action. It should be noted that some of these responding neurons show the same spiking strength between the hidden- and full-vision conditions, while some other neurons respond more under the full-vision condition. Thus it is possible that the firings of different mirror neuron populations convey distinct information; however recordings on individual mirror neurons might be interrupted by neighbor neurons. Future studies via arrayed electrodes combined with computational methods are expected to tell specific individual properties among Mirror neurons.

An fMRI study carried out by Iacoboni^[13] suggested an increased activity of the right inferior frontal cortex (IFC, a part of the MNS) under the intention conditions, further verified the idea that mirror neuron areas participate in understanding the intention of actions. If this area only involves in action recognition, a similar-level response is expected in the inferior frontal cortex when grasping actions were observed, regardless of the context under which grasping actions were

executed. Collectively, these data suggest that the role of the mirror neuron system in coding actions is more complex than what was shown previously, extending from action recognition to the intention-understanding processes. “Out of sight” is not “out of mind” just because, by MNS, the gap can be filled.

Recent evidences further pointed out that the goal-coding capacity, for instance the ability to use tools and integrate them as part of the body, is an intrinsic feature for motor system. Umiltà *et al.*^[14] trained the monkeys to use pliers for grasping food rewards. They found that mirror neurons fire during hand grasping also discharge during grasping with pliers, the situation of which occur both for normal pliers and reverse pliers that require opening the finger to grasp things^[14]. This indicates that the central motor area has incorporate the fliers into part of the body-possibly the extension of finger, like normal or reversed joints, and proves that mirror neurons are directly related to goal-coding process of motor acts.

Action understanding process is important both for personal development process and the evolution of social behaviors. Rizzolatti *et al.*^[1] suggested that mirror neuron mechanism is important for primates to understand actions done by their conspecifics, though this is not the only mechanism through which an individual can understand actions done by others so far. Recently, another finding by Newman-Norlund *et al.*^[15] showed MNS is more active during complementary compared with imitative action, indicating an reliance on specific components of the human MNS during the planning of complementary actions and that MNS activity is important for social cooperating behaviors.

3 Does MNS activity accompany language function?

Little account of human social cognition is meaningful without the involvement of language. Language, especially speech, is one of the most specific hallmarks of what means to be human. The introduction of mirror neuron breathes fresh concepts into this area.

Given that some mirror neurons fire when observing mouth movement which has been regarded as one of the most widely acknowledged origins of language^[7], it is interesting to ask whether mirror neuron system can promote our understanding in how original language could be understood

and how language evolved^[8]. It has been suggested that the mirror system, an observation/execution matching system, provides the necessary bridge from “doing” to “communication”, exchanging the link between actor and observer to a link between sender and receiver of each message. According to the motor theory of speech^[16], sender and receiver must be bound by a common understanding about what counts in all communication; what counts for the sender must count for the receiver, else communication does not occur^[17]. Moreover, the representation of production and perception must, at some point, be the same. Cytoarchitecturally, there are strong similarities between human Brodmann area 44 (the caudal part of Broca’s area) and monkey area F5, the core area of MNS^[18,19].

Bookheimer^[19] and Nishitani *et al.*^[20] indicated that Broca’s region is an exclusive speech production area, containing representations of orofacial gestures and hand actions. With Transcranial Magnetic Stimulation (TMS), Fadiga *et al.*^[21] showed that listening to phonemes induces increased amplitude of the motor-evoked potentials (MEPs) recorded from the tongue muscles involved in their execution. This was interpreted as an acoustically related resonance mechanism at the phonological level. Another complementary TMS study by Watkins *et al.*^[22] showed that listening to and viewing speech gestures enhanced the amplitude of MEPs recorded from the lip muscles. Similarly, Wilson *et al.*^[23] showed the passive listening to phonemes also activate of motor areas devoted to speech production. Further, Watkins and Paus^[24] proved that during auditory speech perception, the increased size of the MEPs obtained by TMS over the face area of the primary motor cortex correlated with cerebral blood flow increase in Broca’s area. Collectively, the activity of MNS with the operating of language areas in human implies an inter-connected relationship might be preserved in our brain during the long process of language evolution.

4 MNS: a bridge between action and language

From the neurobiological perspective, human languages can be conceptualized as repertoires of goal-directed actions shared by all members of a given language community, linguistic actions are viable candidates for the types of actions mediated by a neural circuit for human action understanding. In this sense, language understanding reflects the MNS modulation on the context interaction with previous

experiences, which should influence the excitability of the primary motor cortex, henceforth the production of the movements it controls^[25]. For instance, Meister *et al.*^[26] showed that the excitability of the hand motor cortex increased during both reading and spontaneous speech. It is interesting that this effect is limited to the left hemisphere, and no language-related effect is found in the leg motor area, consistent with the theory that hand signal is another source of language evolution besides mouth movements.

Buccino *et al.*^[27] stimulate either the hand or the foot/leg motor areas in the left hemisphere in distinct experimental sessions when the participants were presented with sentences describing hand or foot actions. They found that MEPs recorded from hand muscles were specifically modulated by listening to hand action-related sentences, which is also the case for foot muscles. In another experiment design, participants have to respond with their hands or the foot when listening to those sentences. Coherently, reaction times of the two effectors are affected by the congruently presented sentences. Additionally, Tettamanti *et al.*^[28] showed that listening to sentences describing actions performed by the mouth, the hands or the foot produce activation on different sectors of the premotor cortex, respectively. Moreover, Gentilucci *et al.*^[29] presented participants with two 3-D objects, large and small. On the visible face of the objects there were either two crosses or a series of dots randomly scattered on the same area occupied by the crosses. Participants are required to grasp the objects, and open their mouth in the conditions that the crosses appeared on the object. The kinematics of hand, arm, and mouth movements showed that lip aperture and the peak velocity of lip aperture will increase when the movement was directed to the large object. All of these experiments suggest that hand gestures and mouth gestures are strictly linked in humans.

In a related study by Gentilucci *et al.*^[30], participants are asked to watch grasping and bringing to the mouth actions while uttering the syllable “GU” or “GA”. They showed that the different actions that the participants observed will influence lip-shaping kinematics and voice formants. The grasping action has an effect on the first formant (which is related to mouth opening), while the observation of bringing to the mouth influenced the second formant of the voice spectrum that is related with tongue movements. Collectively, it seems that during speech acquisition, a process occurred some-

how similar to the one that, in evolution, gave meaning to sound. This mechanism enabled the transfer from a primitive arm gesture communication system to speech. However it should be stressed that the effects on speech were greater in children, implying that MNS is more plastic in developing brains, as is the case for other brain functions.

Arbib suggests that language coevolved with a neuroanatomic-behavioral system, which is specialized for manual gesture production and imitation, and share the same anatomic substrate^[31]. He further pointed out that the region adapted for this purpose corresponds to Broca's area in the human brain and area F5 in the monkey brain, both of which belong to core areas of MNS. Prinz^[32] indicated that the fundamental step of speech evolution was achieved by the improved or metaphysical capacity of action understanding, making it possible to generate the sounds originally accompanied by a specific action without actually doing it. This new capacity may have led to (or derived from) the acquisition of an auditory mirror system, functionally connected to the original audio-visual one, but which progressively became independent of it.

5 The observed rehabilitation therapy

The visual based and auditory based mirror system, once disrupted, result in social behavior defects. Autism was recognized as the MNS dysfunction disorder considering the social and emotional defects in patients: "seeing in not understanding"^[33,34]. Children with autism may have barriers of speech, which is the unique kind of language to human. This raises the possibility of manipulating MNS for treatments of autism children, whose mirror neuron system are likely to be more plastic^[35], indicating a great clinical potential. Online virtual pets, for instance, might provide an easy, simple, inexpensive and fun method that restores MNS function in autistic children^[36]. Many other approaches have been developed^[37], all of which can be easily taught to parents, however still with seemingly benefits. The important function of MNS in action understanding and language formation permit MNS based therapy to be prospective in almost all kinds of language learning disorders or social failure diseases, such as autism. It is hoped that the noninvasive brain manipulation via mirror neuron system will one day lead to more clinical benefits in such patients.

A recent study showed that the motor representations

of mirror neuron could be altered by training^[38], implying that experience-dependent neural system plasticity also exists in mirror neuron system of adult brains^[39]. Thus the utilization of adult plasticity on MNS could be possible for treatments to not only developmental neuropsychological disorders, but also damaged nervous system of adults. It has been hypothesized that action observation as well as imitation could be used as an approach for systematic training in the rehabilitation of patients with motor impairment of the upper limb after stroke^[40], given that many patients suffered from stroke show motor defects^[41]. This has been clinically proved^[42], opening a new avenue to restore brain function beyond physical activity training that is prohibited in many patients who lost their motor abilities.

6 Summary

Mirror Neuron System has been discovered for no more than 20 years. However studies in the past decade brought us more than 500 publications (PubMed) and great improvements in understanding of minds and social brain, as well as exciting clinical applications^[43]. Though single-unit recording on human MNS is still not available, we expect that the translation of basic concepts to clinical application could be promoted further by actual practices. The function of MNS in language appearance and evolution should be further addressed to evaluate the distinct functions of our two hemispheres in language and emotion formation; this may finally lead to improved therapies of mental health problems and other brain disorder diseases.

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镜像神经元系统在动作理解与语言演化中的作用

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摘要: 镜像神经元是近年来认知神经科学领域最为重要的发现之一, 其功能涵盖了动作理解、模仿学习、语言理解、共情、动作预测和语言的进化等多个领域。本文归纳了镜像神经元系统在动作理解和语言交流中的作用, 进一步总结了进化过程中镜像神经元系统介入肢体语言到声音语言的可能性。针对镜像神经元系统的可塑性, 我们讨论了通过调控镜像神经元系统的非侵入性治疗手段对自闭症以及外伤性神经损伤的实用性。

关键词: 镜像神经元; 动作理解; 语言; 康复