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Sensory-motor coupling and its neural mechanisms

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Abstract: *When humans perform sensorimotor tasks, such as practicing a violin piece, it leads to a strong coupling between the sensory cortex and the motor cortex, and this connection and integration between the sensory and motor systems is called sensory-motor coupling. In this paper, we systematically review the concept, manifestations and neural mechanisms of sensory-motor coupling, and review the relevant researches, and find that there is a bidirectional relationship between sensory coding and motor coding, and this coupling between sensory system and motor system has a wide range of manifestations in nature and human society, and there is research evidence at the neural level. Future research should further explore: (1) the association between sensory-motor coupling in audio-visual channels; and (2) channel-based differences in sensory-motor coupling.*

Keywords: *Sensory-motor coupling; Neural mechanisms; Rhythm perception*

1. Introduction

The human brain needs to process and integrate information from different channels, and then guide behavior by generating action instructions. At the same time, the execution of the action will also produce feedback to the sensory system, which will further affect the subsequent perceptual processing. In recent years, studies in psychology [1][2] and neurophysiology [3] have shown that the perception and execution of actions are intrinsically coupled in the human brain, and there is a correlation between actions and their subsequent effects. Sensory-motor coupling encompasses both the process from sensory signal input to the generation of action instructions, and the process by which action execution responds to the sensory system [1][2], which plays an important role in future research on multi-channel information integration. Studies have shown that this form of coupling has at least two possible cognitive functions: First, sensory-motor coupling helps produce equivalent predictions (about when and what events are more likely to occur) during rhythm perception and generation. Second, sensory-motor coupling supports the co-encoding of perception and action, supporting the integration of individual motor output in the context of joint musical tasks.[4] Most fundamentally, sensory-motor coupling plays an important role in supporting human complex (structured) actions and uniting multiple systems to achieve a common goal by predicting and adapting to each other.

Research on sensory-motor coupling can be traced back to the 19th century theory of the principle of action-perception, which held that actions are automatically triggered by expected perceptual effects.[5] However, previous studies have been carried out in the field of behaviorism, until some researchers studied the sensory-motor cycle in the neurological field [6], and after researchers explored the cognitive mechanisms of conscious behavior, the research on sensory-motor coupling gradually became popular. This wave culminated in Prinz's 1990 proposal that perception and motion are encoded in a common representational domain. Since then, researchers have explored sensory-motor coupling mechanisms in many fields such as conceptual movement, action perception and action imitation, interpersonal synchronization, language learning, and empathic response [7], and discovered the mirror neuron system [6], revealing stimulus-response compatibility effects [8], and producing a series of rich research results.

In this paper, we will systematically explain the concept and manifestation of sensory-motor coupling, as well as the neural mechanism of sensory-motor coupling, and evaluate and prospect the current research on sensory-motor coupling. It is of great significance to understand brain function, promote the early diagnosis and intervention of sensorimotor integration disorders such as Parkinson's, and help human beings better carry out social life practice.

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2. Overview of sensory-motor coupling

2.1. Conception

Studies have shown that tempo perception and synchronization tasks, such as practicing piano playing, result in a strong coupling between the sensory (visual or auditory) and motor cortex.[4] Coupling means the phenomenon whereby two or more systems or two forms of movement interact with each other to produce a force increase and work together to accomplish a specific task. Sensory-motor coupling, or perception-action coupling, refers to the connection and integration between the sensory system and the motor system, including the process from the input of sensory signals to the generation of action instructions, as well as the process of action execution giving back to the sensory system, which is a two-way loop connecting the sensory system and the motor system.[1][2]

2.2. Related research

In the real society, people usually need to receive a large number of auditory and visual stimuli, and perceive, process and feedback the stimulus information. This means that the action will cause both a change in proprioception and a change in the environment. Then humans can learn the correlation between action and post-action changes, and then gradually form a two-way connection between motor coding and sensory coding. Once a two-way connection is formed, the individual can choose the action through the sensory after-effects of anticipating or consciously activating an action.[9] Studies have shown that there is a strong coupling between the processes associated with perception and action in the human brain as a result of learning sensorimotor tasks, as evidenced in the brains of musicians.

First of all, in terms of behavioral evidence, some researchers have explored the movement-perceptual connection in music by using action-effect compatibility manipulation. Drost used the interference paradigm to explore the differences between musicians and non-musical trainers who play chords with the piano in response to visual commands. It has been found that inconsistent sounds delay the playing time of piano researchers, but not in non-piano players.[10] In subsequent studies, the researchers asked the pianist to play chords with the guitarist on the instrument, and the interference effect was observed only when the timbre of the music matched the participant's instrument[11]. Taylor's 2014 study also found that when a pianist reacts in the opposite direction of the background scale, they react faster than a novice. The above-mentioned behavioral studies show that if a strong sensory-motor coupling is established after training, then auditory perception initiates action, that is, auditory perception is associated with a specific action, which triggers the representation of a particular action. In addition, at the neurological level, it has also been shown that listening to a trained music sequence activates motor brain regions required to perform the sequence, such as corticospinal cord excitability [12], blood oxygen level-dependent (BOLD) signaling [13][14], and silent visual perception also activates similar motor brain regions, providing empirical evidence for multimodal sensory-motor coupling.

2.3. Manifestations

Sensory-motor coupling plays an important role in human life, and its manifestations are extremely wide-ranging. In nature, animals engage in instinctive foraging behaviors, such as smelling food, which in turn makes mice move closer, which in turn enhances their perception of smell. It can also be seen in motion control involving precision, such as how individuals decide how to grasp the cup based on the perceived size, shape, and relative position, and the occurrence of grasping actions can also make the individual's perception of the characteristics of the cup more accurate.[4] Sensory-motor coupling also plays an important role in the learning of complex skills such as language and music. For example, in piano playing, the musician's perception of the duration of the tone guides the key action, and the auditory effect produced by the key action is used to correct the execution of the next movement.

3. Neural mechanisms

In fact, human beings learn all kinds of actions without the establishment of sensory-motor coupling. The action occurs to cause both changes in proprioception and changes in the environment. Individuals can learn the associations between movements and these subsequent changes, gradually forming a two-way connection between motor and sensory coding. Once a two-way connection is formed, individuals can choose actions through the perceived after-effects of anticipating or intentionally activating an action.

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Traditional approaches to human information processing tend to deal with perception and action plans in isolation, lacking an adequate explanation of the perceptual-motor connection. In terms of perception, the dominant cognitive view largely underestimates the impact of action-related processes on perceptual information processing and perceptual learning; In terms of action, most approaches consider the action plan to be merely a continuation of the stimulus treatment, but this does not explain the goal orientation of the simplest response in the experimental task [7]. Therefore, a new theoretical framework is needed to reconstruct the perceptual-motor connection. Researchers have developed a more adequate theoretical approach to perception and action action by proposing a co-coding theory [7]. The theory suggests that perceptual content and action plans are encoded in a common representational medium by feature codes with distal references. The perceived events (perceptions) and the events that will be generated (actions) are likewise represented by an integrated, task-tuned network of feature code (cognitive structures of the event code). That is to say, sensory events and planned actions share a common representation, and the actions are encoded according to the perceptual effects they may produce; The associated sensations and actions can be activated and influenced by each other. The sensory code formed by the stimuli in the environment and the behavioral code generated by the brain control body together constitute the sensory representation domain. The two codes are transformed in the same place, thus completing the connection between the perceptual event and the action, and the connection between the two enables the behavior to be adjusted and controlled according to the perceived effect. In the past, the induction paradigm and the interference paradigm were mostly used to explore the connection between perceived events and actions. The purpose of the induction paradigm is to enhance behavior by inducing similar perceptual events, so as to reveal the details of the co-coding theory in the temporal and spatial domains.

The interference paradigm is the study of how perceptual events and behaviors interfere through similarity.There is research evidence for the co-coding theory in sensory-motor coupling studies at the neural level. At present, researchers have explored the sensory-motor coupling mechanism in many fields such as conceptual movement, action perception and action imitation, interpersonal synchronization, language learning, and empathic response [7], and produced a series of rich research results. At the neural level, the researchers found that fMRI signals and brain activity are similar when perceiving and performing actions through cross-modal classification. This provides direct evidence that the activity patterns of pre-motor voxels with sensory properties are important sources of information about the nature of these behaviors when perceiving the actions of others, and that such information shares a common code with motor execution, suggesting that perceptual information and action execution can be represented using a common representational code. [15]

The discovery of the mirror neuron system provides a potential neural basis for the simulation and general coding theory of action perception, and further provides a neuro-based explanation for sensory-action coupling.[3] The mirror mechanism argues that we understand the behavior of others because the perception of others' behavior activates some of our own neurons, providing a basic mechanism for unified action generation and action observation, allowing for understanding the actions of others from the inside. The researchers found that a specific circuit with mirror properties, the parietal-frontal mechanism allows an individual to understand the behavior of another individual "from the inside" and allows the observer to grasp the movement goals and intentions of another individual in a first-person manner. When one person observes another person doing an action, a group of neurons encoding the action is activated in the observer's cortical motor system.

4. Conclusions

Although sensory-motor coupling has attracted the attention of psychologists and neuroscientists, few studies have been conducted on the channelability differences and interchannel-related associations of sensory-motor coupling. Exploring the channel-based differences and inter-channel associations of sensory-motor coupling not only has important basic research value, but also promotes the early diagnosis and intervention of sensorimotor integration disorders such as Parkinson's disease.

Parkinson's disease is a chronic neurodegenerative disease caused by the loss of basal ganglia cells, one of the main manifestations of which is sensorimotor integration disorder, and studies have shown that audio-motor beat synchronization training is more helpful than visual-motor beat synchronization training in gait recovery in Parkinson's patients [16][17], but there are also studies that show that Parkinson's patients are more dependent on vision, and that visual cues help Parkinson's patients initiate movements, maintain a rhythmic gait, and reduce the risk of falls.[18] Determining the dominant stimuli of sensory-motor coupling in audio-visual channels and exploring the neural basis of channel-based differences in sensory-motor coupling can provide a theoretical basis for the training design of physical therapy for

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Parkinson's disease.

Firstly, to explore whether there is a difference in the intensity of sensory-motor coupling between audiovisual channels, it is helpful to understand the weight distribution of information integration among multiple channels. In real life, people will involuntarily follow the rhythm of the music to synchronize the beat, which is what we often call beating, and even some individuals have difficulty suppressing this synchronization impulse. This suggests that auditory rhythm has a strong inducing effect on synchronized movements, revealing the close connection between the auditory and motor systems [19]. At the same time, some researchers have found that the stability and accuracy of following visual stimuli for beat synchronization are far worse than those of auditory stimuli, and the phenomenon of following visual information for beat synchronization is relatively rare in real life, so there is a consensus on "auditory channel specificity" in related fields, and it is speculated that the reason may be that the intensity of people's auditory-motor coupling is higher than that of visual-motor coupling[20][21]. However, the recent "effective ball effect" has challenged the consensus in the field, with studies showing that tempo synchronization with visual motor stimuli can achieve the same level as auditory stimuli.[22] Therefore, the channel-based differences between visual-motor coupling and auditory-motor coupling are still unknown, and relevant empirical studies are needed to further advance.

Secondly, exploring the association of sensory-motor coupling in audio-visual channels can help understand whether sensory-motor coupling is carried out in a way that is common to all channels, and further provide scientific guidelines for the improvement of tempo synchronization performance in real-world situations and the early diagnosis and intervention of sensorimotor integration disorders such as Parkinson's.[16] Sensorimotor coupling ability and rhythm perception ability are two important aspects that affect tempo synchronization, and it has been found that auditory training can significantly improve visual rhythm perception, and visual cues can also promote the anti-interference level of auditory rhythm perception.[23] The above findings suggest that the time perception of the audiovisual channel is based on a common timing mechanism. Visual-motor coupling and auditory-motor coupling are not completely independent, and the two may be linked according to some mechanism. However, in addition to temporal perception, it is not yet known whether the sensory-motor coupling, another aspect that supports tempo synchronization, is independent of each other in the audiovisual channels. The dual-pathway model theory of the sensory system divides the sensory pathway into ventral pathway and dorsal pathway, and the visual system and auditory system are connected to the motor system through these two pathways. Among them, spatial processing in visual and auditory modalities includes the processing of spatial movement over time. The dorsal pathways of the visual and auditory systems are able to preserve not only the activity of the neuronal assemblage for a limited time, but also the temporal sequence of sensorimotor events. The combination of these two features explains the association process between sensory events and movement, and provides support for the theory of the connection between the auditory system and movement.

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