DOI:10.6129/CJP.202006_62(2).0007
中華心理學刊 民 109，62 卷，2 期，245-266
Chinese Journal of Psychology 2020, Vol.62, No.2, 245-266

Sport Cognitive Neuroscience: Present and Future

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Athletic performance is closely related to brain mechanisms. Sport cognitive neuroscience, an area of research utilizing brain imaging tools for the understanding of potential in human motor performance with roots in psychophysiology, has incorporated sport psychology theories and neuroscience techniques to evolve as a distinct research field. Research topics in this field mainly focus on the relationship between neurocognitive processing and athletic performance by recording the neural activity with brain imaging tools, particularly with electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). This paper reviews relevant research on sport cognitive neuroscience with an emphasis on work conducted by local researchers. An overview of the evolution and theories of sport cognitive neuroscience is provided, as well as exploration of studies categorized by the cross-sectional and longitudinal design in sport cognitive neuroscience using EEG and fMRI. Lastly, the unresolved issues in the previous studies are discussed, with suggestions for future studies.

Keywords: *concentration, EEG, fMRI, interference, performance in precision sports*

Extended Abstract

Sport Cognitive Neuroscience is an emerging research field that aims to understand the role of the brain in maximizing human physical potential (Carlstedt, 2018). There are two main theories that explore the relationship between brain activity and motor performance: the “neural efficiency hypothesis” and the “multi-action plan” (MAP) model (Bertollo, Hanin, & Robazza, 2012; Haier, Siegel, Tang, Able, & Buchsbaum, 1992; Hatfeild & Hillman, 2001). Based on the neural efficiency hypothesis, Hatfield and Hillman (2001) put forward the psychomotor efficiency hypothesis, which proposes that skilled athletic performance is characterized by a reduction in the number of “motor units” recruited by the central nervous system. The MAP model, in contrast, categorizes motor performance into four types with varying levels of efficiency and performance. Type 1 performance is characterized by optimal performance in an effortless and automated attentional state, and exemplifies high psychomotor efficiency (Hatfield, 2018). Type 2 performance is typified by high-level performance effectiveness but low processing efficiency. Type 3 performance reflects both low-level performance effectiveness and low processing efficiency and is characterized by excessive reliance on controlled processing, which results in working memory overload. Type 4 performance is a suboptimal automatic state with minimal reliance on working memory (Bortoli et al., 2012). Although there is some preliminary support for these two theories, issues relating to the cortical processes and mechanisms underlying optimal and suboptimal performance remain to be addressed. Different neuroimaging tools need to be applied to provide data from multiple perspectives.

Neural Measurement Tools

Recent cognitive motor neuroscience research mainly relies on neuroimaging tools such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), as these methods have the advantages of high-temporal resolution and high spatial resolution, respectively. EEG measures the electrical activity of the brain. EEG analysis can be divided into three types: “frequency domain,” “time domain” and “space-oriented” analyses. Frequency domain analysis usually involves decomposing brain waves into spectral power frequencies by Fourier transform, followed by statistical testing to examine differences between groups or conditions according to the purpose of the study. Time domain analysis is mostly based on event-related potential (ERP) analysis. Space-oriented analysis calculates the source of the brainwave signal using mathematical models and biophysics with corresponding brain functions to understand the Brain’s spatial dynamics of information processing during the task.

fMRI is a neuroimaging technique that combines magnetic resonance imaging and hemodynamics to measure brain activity in a non-invasive way. Magnetic resonance imaging can be used to analyze both brain structure and function. Brain structure analysis mainly measures the density or volume of gray matter and the white matter covering the nerve fiber bundles. Brain functions are divided into task-related and resting-state functions. Sport cognitive neuroscience research compares the brain images of athletes of different skill levels to examine the changes in brain structure and function that occur as a result of motor skills training（Scholz, Klein, Behrens, & Johansen-Berg, 2009; Draganski et al., 2014）. This area of research aims to understand the neural mechanisms underlying superior motor skills and has implications for expediting motor skill learning and improving sports performance.

Sport Cognitive Neuroscience Studies

The neural plasticity resulting from sports training and motor skills learning has become an important research topic. This review is organized according to the different methods of analysis used in EEG and MRI research.

EEG studies

1. Alpha frequency

Hatfield, Landers, and Ray (1984) pioneered to use EEG to study the antecedents of motion performance in professional rifle shooters. They found that the alpha power (8-12 Hz) of the left-temporal area progressively increased as the shooter approached the trigger pull. This observation was interpreted as indicating a reduction in verbal-analytical processing, which is not essential to shooting execution, to increase concentration. Studies from other sports have provided convergent evidence for the close relationship between alpha power in the preparation phase, particularly in the left temporal area, and superior motor performance in precision sports such as shooting, archery, and golf (Salazar, Landers, Petruzzello, Crew, & Kubitz, 1990; Hung, 2000; Kerick et al., 2001). Moreover, it has been suggested that high alpha (10-12 Hz) is a distinctive component of the broad alpha band for determining optimal performance (Haufler, Spalding, Santa Maria, & Hatfield, 2000; Baumeister et al., 2008; Bobiloni et al., 2008).

2. Theta frequency

Theta power is measured in the 4 to 7 Hz bandwidth. In sports, theta power in the medial prefrontal cortex is related to the preprocessing of “top-down” attentional control. Some studies have found that compared with beginners, expert athletes in precision sports show higher frontal midline theta power, indicating more sustained attention, in the preparation period (Haufler et al., 2000; Baumeister et al., 2008; Doppelmayr et al., 2008). However, some intra-individual studies comparing good and poor performance have shown the reverse: greater frontal midline theta power preceding poor performance in experts (Kao et al, 2013; Chuang, Huang, & Hung, 2013). These results suggest that excessive attentional control may undermine automaticity. Despite the heterogeneous findings from expert-novice and intra-individual study designs, a close and complicated relationship between frontal midline theta and sports performance can be assumed, although more studies are needed to examine possible moderators.

3. SMR rhythm

The sensorimotor rhythm (SMR) refers to the 12 to 15 Hz frequency band located in the sensory-motor cortex and has been interpreted as a measure of the efficiency of motor movements (Sterman, 1996). A higher SMR power has been linked to superior performance in sport. The higher SMR power in expert athletes results in the filtering out of non-task-related information processes, and reflecting the reduced interference of sensory movements during the preparation period (Cheng et al., 2015a). Moreover, the data from an intra-individual study found that a higher SMR power was associated with better sport performance (Cheng et al., 2017). These results suggest that during preparation in precision sports, the SMR may be an important indicator of the adaptive adjustment of cognitive-action processes.

4. Coherence study

Coherence analysis computes the correlations between different electrodes to measure the level of cortico-cortical communication (Boersma et al., 2011). Greater coherence implies higher connectivity between two brain regions, while low coherence indicates regional autonomy (Nunez & Cutillo, 1995; Weiss & Mueller, 2003). In studies of precision sports, reduced EEG coherence between left temporal and frontal areas has been interpreted as indicating less interference from verbal-analytical processes prior to superior performance, which is consistent with the psychomotor efficiency hypothesis that experts use neural resources more efficiently to produce better performance than novices (Wu, Lo, Lin, Shih, & Hung, 2007; Cheng et al., 2017; Chuang et al., 2010).

5. Event-related potentials (ERPs)

ERPs are time-locked EEG components that reflect specific neural processes elicited by an experimental paradigm (Luck, 2014). Previous studies have revealed differences in attention (Strayer & Kramer, 1990) and inhibitory control (Dietrich & Kanso, 2010) when comparing experts and novices on a Go/No-Go task. Hung et al. (2004) reported that table tennis experts demonstrated not only effective allocation of attention but also more efficient motor preparation in highly uncertain conditions, reflecting a strategic deployment of response resources for better adaptation to the environment. These intricate cognitive processes are consistent with the psychomotor efficiency hypothesis.

6. Other analytic methods

Dimensional complexity was an early nonlinear method used to examine cortical activity changes (Hebb, 1949). Experts have higher neurological efficiency than novices, while lower neuronal complexity may be associated with lower motor-related neural interference (Hung, Haufler, Lo, Mayer-Lress, & Hatfield, 2008). Despite the demonstrated association with superior sports performance, further studies are needed to explore how this finding can be translated into improved sports performance.

fMRI studies

Motor skill learning can induce changes in brain structure. Most studies using fMRI have found that gray matter volume and white matter connection strength in action-related brain regions increase with training experience (Jacini et al., 2009; Schlaffke et al., 2014; Hänggi et al., 2015). However, different sports require different specialized skills and few studies have explored the influence of various motor skills on the human brain. Further longitudinal studies are therefore needed to clarify the neural plasticity mechanism.

In motor anticipation tasks, fMRI studies (Balser et al., 2014a; Balser et al., 2014b; Caspers, Zilles, Lairs, & Eickoff, 2010) have demonstrated that experts display greater cortical activity in the "action observation network," reflecting more efficient reorganization of neural resources that results in rich motor observation and execution experience. Conversely, novices need to recruit more neural resources to suppress task-irrelevant information (Bishop, Wright, Jackson, & Abernethy, 2013; Kim et al., 2014; Milton, Solodkin, Hluštik, & Small, 2007; Wei & Luo, 2010; Wright, Bishop, Jackson, & Abernethy, 2013). The ability of experts to efficiently allocate neural resources is consistent with the psychomotor efficiency hypothesis.

Longitudinal studies

Sport cognitive neuroscience studies based on longitudinal designs have mainly focused on motor skill learning and neurofeedback training (NFT), a selfregulation method that participants learn to control their neural signals such as EEG by the provision of feedback.

Alpha power is generally considered an indicator of cortical inhibition. During movement execution, higher alpha power in the left temporal region has been interpreted as indicating reduced verbal-analytic processing (Haufler et al., 2000). However, the findings of NFT to increase alpha power have been inconsistent, possibly due to methodological differences in NFT across different studies (Landers et al., 1991; Dekke, Van den Berg, Denissen, Sitckoorn, & Van Boxtel, 2014).

Theta power, especially at the frontal midline site, has been associated with top-down attention. Kao, Huang, and Hung (2014) revealed that improved golf putting performance was observed following NFT to down-regulate frontal midline theta. The authors suggested that the lower frontal midline theta leads to reduced top-down attention control and is believed to reflect effortless mental operations.

Cheng et al. (2015b) demonstrated that up-regulation of SMR by NFT results in higher SMR during the preparation phase and improved putting performance in expert golfers. The association between higher SMR and superior motor performance is the most consistent finding supported by cross-sectional studies, intraindividual studies comparing good and poor performance, and NFT intervention studies. Future studies might further examine the generalizability of SMR to other precision sports and how psychological factors such as anxiety, self-confidence, and arousal interact with SMR.

A recent intervention study by Lo, Hatfield, Wu, Chang, and Hung (2019) confirmed the above findings of lower coherence, especially in the high alpha band, between the left temporal and frontal areas among highly skilled and superior performing participants. They demonstrated that laboratory-induced stress resulted in heightened coherence in the high alpha band between the left temporal and frontal areas, which subsequently impaired dart throwing performance in a group of skilled participants. These findings imply that coherence between the left temporal and frontal areas is a reliable indicator of superior motor performance. Future studies may explore coherence between other brain regions to better understand the relevant and irrelevant neural networks underlying superior motor performance.

Although fMRI provides millimeter-precise spatial resolution superior to EEG, the participant is limited to a lying posture during brain scanning. Hence, most fMRI studies use motor imagery training to detect changes in participants' motor systems (Hwang, Velanova, & Luna, 2009; Chiew, LaConte, & Graham, 2012; Ba, Huang, Fei, & Kunz, 2014; Boe et al., 2014). In a motor skill learning study, Bezzola, Mérillat, Gaser, and Jäncke (2011) found increased gray matter density in the motor-related brain regions of learners. Furthermore, the training intensity was positively correlated with gray matter density, which displays a close relationship between motor skill learning and brain plasticity.

Conclusion and Suggestions for Future Research

Studies have shown that several EEG components at specific brain regions are closely related to motor performance in precision sports. Similarly, fMRI studies have shown that experts have high neural efficiency in the motor cortex. Nevertheless, these reviewed studies were limited by (1) relatively small sample sizes, (2) uncontrolled possible confounders, (3) lack of a standardized definition of skill level, and (4) the lack of a control group in longitudinal studies. Accordingly, future studies are advised to (1) compare different sports, (2) establish standardized steps for neurofeedback training, (3) consider individual differences, (4) enhance ecological validity by moving from the lab to the field, (5) apply novel neuroimaging tools, and (6) co-register several measurement tools.