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Review article

Neurofeedback as supplementary training for optimizing athletes' performance: A systematic review with implications for future research

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ABSTRACT

Self-regulation plays an important role in enhancing human performance. Neurofeedback is a promising noninvasive approach for modifying human brain oscillation and can be utilized in developing skills for self-regulation of brain activity. So far, the effectiveness of neurofeedback has been evaluated with regard to not only its application in clinical populations but also the enhancement of performance in general. However, reviews of the application of neurofeedback training in the sports domain are absent, although this application goes back to 1991, when it was first applied in archery. Sport scientists have shown an increasing interest in this topic in recent years. This article provides an overview of empirical studies examining the effects of neurofeedback in sports and evaluates these studies against cardinal and methodological criteria. Furthermore, it includes guidelines and suggestions for future evaluations of neurofeedback training in sports.

Contents

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1. Introduction

In recent systematic reviews, the effectiveness of neurofeedback has been evaluated not only with regard to its application in clinical populations, but also for enhancement of performance in general. In these reviews, however, an interesting application field of neurofeedback training has been completely neglected—sports psychology. An essential element for stabilizing and enhancing sports performance is to promote self-regulation skills in athletes; for example, relaxation and concentration skills (Beckmann and Elbe, 2015). Because biofeedback in general (Cashmore, 2008) and neurofeedback in particular are assumed to provide direct routes to self-regulation, they have also attracted professionals and researchers who attempt to enhance athletes' performance. The aim of this review is to provide an overview of studies evaluating the effectiveness of neurofeedback training (NFT) to enhance athletes' performance and to scrutinize methods and results of these studies.

The article is structured as follows. First, we outline the nature of neurofeedback and describe electrical brain activity. Knowledge of essential elements of electrical brain activity provides better understanding of its relationship with mental states and recognition of neurofeedback protocol differentiation. Then a brief history of neurofeedback and its application, both in general and in particular to sports, are provided. Subsequently, the method for searching and scanning articles and the criteria for inclusion in and exclusion from the review are outlined. The included articles are presented and classified based on researchers' protocols. Results of previous studies are then presented and discussed to answer the research questions. Finally, we discuss conclusions based on the reviewed evidence and suggest some future research focused on promoting NFT's application for fundamental skills in sports.

1.1. Nature of neurofeedback and electrical brain activity

Biofeedback is based on the observation that, whereas a person usually cannot intentionally modify autonomic functions, individuals are able to regulate these biological functions once they have greater access to detailed information about their signals (Lawrence, 2002). To this end, in biofeedback, psychophysiological signals of autonomic functions are transformed into external signals. These signals are "fed back" to the individual who can learn to change and influence them (Strack and Sime, 2011). Control over physiological processes is thought to be acquired through an operant conditioning principle (Hammond, 2011).

One example of feeding back psychophysiological information is neurofeedback, in which a person is made consciously aware of his or her brain activity. Activity of the brain can be measured through different signals, for example, blood flow, oxygen consumption, or electrical activity, and each signal may be used for feedback. Still, recording and feeding back electrical activity through electroencephalography (EEG) remains the traditional, common form of neurofeedback (Hammond, 2011). This review therefore focuses on "EEG biofeedback training," and we use "NFT" interchangeably with it.

EEG is most commonly recorded from the scalp's surface, and it records currents in the cerebral cortex that develop during synaptic excitations of the dendrites of pyramidal neurons. Synaptic currents are generated within dendrites, once neurons (brain cells) are activated. EEG signals are formed through ionic flow from large groups of dendrites due to synaptic transmission, and the alternation between excitatory and inhibitory postsynaptic potentials in these synapses produce the familiar oscillatory signal in the EEG (Sanei and Chambers, 2007). The EEG allows recording of activities with a roughly 5 cm cortical surface spatial resolution (1 mm deep, 100+ million neurons) and high temporal resolution, allowing for direct studies of brain dynamic function at millisecond time scales (Ullsperger and Debener, 2010).

The human brain is never at rest, and EEG of the cerebral cortex shows spontaneous activities that vary in frequency (Zagha and McCormick, 2014). The EEG signal may be analyzed in the frequency domain, and frequencies in the EEG signal are commonly distinguished by five major EEG bands, presented in Table 1, from high to low frequency (Gruzelier and Egner, 2004). Since the appearance of EEG, research has attempted to identify relations between electrical brain activity and frequency bands on the one side and mental states on the other. Early research, for example, identified the Alpha range related to a state of relaxed attention (Klimesch, 1999). Clinical research identified over-activation in the Theta range in attention deficit/hyperactivity disorder (Lubar and Shouse, 1976). Spontaneous EEG activity has also been linked to performance requirements; for example, performing an attention-demanding task is related to greater EEG activity in the sensory motor rhythm (SMR) range. In the sports field, such relations of electrical brain activities and mental states of optimal performance have also been examined. It has been argued, for example, that when a person performs a well-practiced, over-trained task, elevated power in the Alpha band may be found (Alpha synchronization), reflecting decreased cortical information processing. Such an observation matches the "automatic" rather than the "cognitive" stage of sensorimotor skill acquisition theory, according to Fitts and Posner (Mierau et al., 2015).

To summarize, neurofeedback applies EEG to record and feed back the brain's electrical activity. The EEG signal is composed of different frequencies that may be organized into different frequency bands. Each band is thought to reflect different brain states and may be associated with different behavior and behavioral outcome (performance). Now, the idea of neurofeedback is to teach individuals to regulate brain activity within a frequency band to enhance the associated mental state or behavior. For the design