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Neurofeedback as Supplementary Training for Optimizing Athletes' Performance: A Systematic Review with Implications for Future Research

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Highlights

- It is time for the evaluation of NFT in sport domain.
- Evidence for specific protocols' effectiveness in enhancing performance is weak.
- Developing NFT interventions in an applied setting in sport appears premature.

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.

Keywords: Neurofeedback, Athlete, Sports performance, Cognition, Affect

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 of appropriate NFT, this implies that the relationship between the electrical brain activities and specific-task needs is determined a priori.

1.2. A brief history of neurofeedback

The root of neurofeedback (NF) traces to the 1960s when it was shown that humans can train to exhibit dominant brain activity in the Alpha range (Kamiya, 1962). Simultaneously, cats were shown to produce dominant activity in the low Beta range (or SMR) at a specific moment through operant conditioning (Wyrwicka and Sterman, 1968). NF, as an alternative to pharmacological treatment, was linked to the medical realm when Sterman used NF as a treatment for a group of astronauts and service personnel who were exposed to rocket fuel and suffered from headaches, nausea, and seizures (Larsen and Sherlin, 2013). He decided to increase power in the range of 12–15 Hz (SMR). He had found that cats previously trained in his laboratory showed more resistance to seizures than those not trained. The positive effect of SMR training was very quickly replicated for treatment of epilepsy by other researchers. These findings encouraged yet other researchers to begin looking for dimensions of regulating the brain through NF. For instance, Lubar and Shouse (1976) found that through NF, they could help children who suffered from ADHD by regulating their brain patterns. In comparison to normal persons, this group normally shows an imbalanced brain wave pattern, that is, high activity in the Theta range and low activity in the Beta range over the left temporal lobe. Thus, researchers decided to increase power in the SMR range and adjacent frequencies and at the same time inhibit activity in the Theta range (Lubar and Shouse, 1976). This experiment was the first to apply inhibition functions with an obvious purpose concerning balanced distribution of brain waves (Budzynski et al., 2009).

Today, there is a large body of evidence for the efficacy of NFT (e.g., see Gruzelier, 2014a). There is also evidence for the stability of neurophysiological changes after NFT

(Becerra et al., 2006; Gevensleben et al., 2010; Kouijzer et al., 2009). These changes are assumed to be based on the brain's neuroplasticity mechanisms (Ninaus et al., 2015). Magnetic resonance imaging (MRI) assessment has confirmed that changes in brain activity after NFT are associated with microstructural changes in the white and gray matter (Ghaziri et al., 2013) that generally occur in the gyrus and cerebral cortex. Especially with regard to gray matter, these changes can indicate the brain's potential to undergo neuroplasticity. Gray matter volume has been linked to learning a task successfully (Ninaus et al., 2015). So it appears that NFT can lead to better cognitive processing and learning via enhancement of the conduction velocity in neural networks by modifications in white matter pathways and gray matter volume.

NFT has also been applied to enhance performance. For instance, increasing power in the SMR range led to better accuracy and speed in surgery skills (Ros et al., 2009), inhibition of power in the Theta range decreased the number of errors in radar detection tasks (Beatty et al., 1974), increasing power in the mid-Beta range and inhibition of the Theta range resulted in faster reaction time in an attention task (Egner and Gruzelier, 2004), and increasing power in the high Alpha range led to better memory function (Escolano et al., 2011; Zoefel et al., 2011).

Furthermore, NFT has been applied to enhance athletes' performance. In the pioneering study by Landers et al. (1991), archers received NFT to improve their shooting performance. The intervention was based on profound understanding of the task and associations between brain activation and performance in the task. Previous studies (Hatfield et al., 1984; Salazar et al., 1990) had shown that good execution in archery was associated with activation in the brain's right hemisphere, which is associated with visual-spatial processing, and, at the same time, decreased activation in the left temporal lobe. This decrease in activation in left temporal areas and specifically in verbal-analytic areas was associated with reduction of attention to stimuli and suppression of irrelevant information. Thus, Landers et al. (1991) hypothesized that performance should improve if activation in the left hemisphere were suppressed. Results confirmed these expectations and showed an increase in archery performance in the group of archers that received NFT to decrease left temporal activation, compared to the group that received NFT to decrease activation in the right hemisphere.

Extensive research has been conducted on NFT for treating psychological disorders, and it has been highlighted in reviews and meta-analyses (e.g., Arns et al., 2009; Coben et al., 2010; Moore, 2000; Tan et al., 2009). Recently, a considerable series of review studies have also focused on optimizing performance through NFT (e.g., Gruzelier, 2014a, b, c). Notwithstanding the seminal successful examination of NFT in archery by Landers et al. (1991), studies on NFT application to improve sports performance are still scarce. Despite recent reviews providing evidence for the effectiveness of NFT in clinical applications, surgery, and music performance, no such reviews exist regarding application in sports.

1.3. This review's aim

Neurofeedback training appears to be a powerful tool for training performance-enhancing self-regulation of brain states. As such, it has been deemed useful for improving sports performance. However, although the application of NFT to improve athletes' performance has been described since 1991, no review assessing its effectiveness in sports exists until today. Even in the latest general review by Gruzelier (2014a), the specific field of sport performance was not subject to scrutiny. Given the search for evidence-based interventions in sports psychology, such a review is needed. NFT interventions to improve sports performances should not solely rely on findings from other fields of application because of differences between the athletic population and the clinical or even general population (Del Percio et al., 2008; Iwadate et al., 2005). Furthermore, the objective of NFT differs between athletes and clinical samples because athletes aim to improve their performance, whereas patients are interested in treating some negative condition (Wilson and Peper, 2011). Thus, determination of whether results can be transferred from other populations to athletes is required. In the advent of more mobile devices for EEG assessment (Park et al., 2015), it also appears to be time to provide guidelines for future research that can lay foundations for NFT sports applications.

1.4. Research questions

This review has three aims. The first is to provide an overview of empirical studies investigating the effectiveness of NFT in sports. The second is to evaluate findings against methodological and theoretical criteria. This evaluation should entail conclusions regarding evidence of NFT's effectiveness for improving sports performance. The third aim is to provide guidelines and suggestions for future NFT evaluations in sports.

2. Methods

A systematic review was conducted using PRISMA methodology. Its main aim was to find NFT related to athletes' performance. Therefore, we primarily sought to retrieve studies that explicitly used the following search terms: "EEG biofeedback AND athlete OR sport OR performance," "Neurofeedback AND athlete OR sport OR performance," and "Slow Cortical Potential AND athlete OR sport OR performance." A comprehensive, yet systematic search of the following seven databases covering most scientific fields was conducted: Scopus, Science Direct, PubMed, Google Scholar, PsycINFO, SPORTDiscus, and Web of Science.

2.1. Sifting retrieved studies

The retrieved studies were sifted in two stages: results were first reviewed by title and abstract and then by full text. At each step, studies that did not comply with the review's inclusion and exclusion criteria were deleted. Studies included in this review had to be 1) using original empirical, primary evidence/data; 2) published (either in a paper or in an online peer-reviewed scientific journal); 3) in English. Studies were excluded from this review if a complete report of their methods (especially the selected frequency and location of electrodes) was not offered.

2.2. Search returns

The search process, finalized on June 30, 2016, initially returned **30** potentially relevant studies. After duplicates (one study) and abstract studies (three studies) were eliminated, the abstracts and methodology of the remaining potential target papers (n = **26**) were assessed. Further 12 studies had to be eliminated for lack of complete report of methods, thus reducing the potential targets to 14 articles.

2.3. Organization of results

These 14 empirical studies were further organized according to the applied neurofeedback protocol and type of outcome variable. As most studies used a combination of protocols and some studies measured different types of outcomes, a study could be assigned to multiple categories. Furthermore, to detect possible effects of moderators, studies were also classified according to moderators. In addition, in order to present a comprehensive overview over the literature the results of the 12 practical reports will also be presented.

2.3.1. Neurofeedback Protocol

To apply NFT, a therapist or researcher has first to determine the frequency band that is to be trained and also the brain area from which frequencies are recorded. In NFT, a "protocol" defines the training frequency (or frequencies) and the site of the recording electrode(s).

As presented in Table 1, brain frequencies are conventionally subdivided into fixed frequency bands such as Theta (4–8 Hz) or Alpha (8–12 Hz). The most common procedure for NFT is to select one (or more) of these frequency bands, based on theoretical consideration or previous empirical evidence. Training a frequency band can consist of increasing or inhibiting the respective band's amplitude.

Beyond such common protocols, other, more individualized protocols exist because EEG assessment shows that the relation between brain frequencies (and bands) and mental states may vary as a function of various factors such as age. For the Alpha band, for example, even age-matched participants have been found to show significant variability in Alpha frequency. Therefore, NFT protocols sometimes assess and feed back brain activity based on the Individual Alpha Frequency (IAF; for a more detailed description see the review study by Klimesch, 1999).

A further step toward an NFT individualized protocol is based on "Personalized event-locked EEG-profile." For such a profile, first, cortical activity associated with the best and worst performance during task execution in a baseline condition is assessed. The performer receives customized neurofeedback based on this comparison in a second step.

Whereas classic NFT aims at specific frequencies, the training of slow cortical potentials (SCP) aims more generally at the excitability level of cortical and subcortical areas. SCP are EEG's direct-current shifts that last from a few hundred milliseconds to seconds. Excitation of rather large cortical areas relates to surface-negative SCP that occur during behavioral and cognitive preparation. In contrast, decreased excitation underlying cortical areas relates to surface-positive SCP observed during behavioral inhibition. Through SCP training, participants learn to regulate cortical excitability and change between an activated/attentive state and a deactivated/relaxed state by modulating their SCP toward more negative and positive amplitudes, respectively.

Location of electrodes on the scalp usually follows the International 10–20 system, in which a letter identifies one of five areas of the brain, and numbers identify the brain hemisphere. The letters F, T, P, and O stand for frontal, temporal, parietal, and occipital lobes, respectively. The letter C stands for the central area. A "z" refers to an electrode placed on the midline (from Nasion to Inion). Even numbers refer to electrode positions on the right hemisphere, odd numbers refer to those on the left hemisphere. Thus, for example, C3 refers to electrode location in the left hemisphere at the central area (line between auricular points).

2.3.2. Outcome Variables

The main concern of sports training is optimizing performance. Thus, the main research question addresses NFT's effectiveness in improving athletes' performance (e.g., changes in golf putting accuracy). Still, other outcomes have also been the target of intervention studies that may be recognized as prerequisite or mediating factors related to performance. These outcomes were classified into affective (e.g., changes in performers' level of anxiety or stress) and cognitive (e.g., changes in an attention test) outcomes.

2.3.3. Moderator variables

Evaluating NF studies may be especially fruitful when examining moderators' probable effects. Gender and experience were chosen among all possible moderators in this review because they have been mostly reported as demographic information. Additionally, there is considerable debate regarding gender differences as well as the level of participants' expertise and NFT's effectiveness.

3. Overview of empirical studies on NFT in sports

This review's first aim is to provide an overview of empirical studies that have investigated the application and effectiveness of NFT interventions in the sports domain. Despite a wealth of studies in other, especially clinical, domains, our research result yielded only 13 studies after the seminal study on archers by Landers et al. in 1991. An overview of these studies' distribution, results, and characteristics is provided in Table 2.

3.1. Results

3.1.1. Beta band

Four of 14 studies applied NFT in the Beta-band, and two intended to improve sports performance directly. Inhibiting high Beta (20–30 Hz) and concomitantly increasing SMR (13–15 Hz) at C3 and C4 sites led to better performance in rifle shooting in an experimental group compared to a control group (Rostami et al., 2012). However, inhibiting high Beta (22–26 Hz) and Theta (4–7 Hz) while increasing SMR (12–15 Hz) at the Cz site in archery did not have a significant effect on performance in an experimental group (Paul et al., 2011).

Even so, inhibiting high Beta (22–37 Hz) and increasing mid Beta (15–18 Hz) at C3 and C4 sites in swimming led to reduction and improved regulation of anxiety in the experimental group (Faridnia et al., 2012). Moreover, inhibiting high Beta (21–35 Hz) and Theta (4–7 Hz) while increasing mid Beta (15–20) at C3 and C4 led to significant changes in the levels of autotelic engagement in the experimental group compared to the control group (Mikicin, 2015). The experimental group also exhibited significant enhancement in variables of a mental arithmetic test ("work curve test") compared to the control group (Mikicin, 2015).

3.1.2. Sensorimotor rhythm (SMR)

Six of 14 studies applied NFT in the SMR band, and four of these studies applied SMR to improve performance. As mentioned above, increasing SMR (13–15 Hz) concomitant with inhibiting high Beta (20–30 Hz) at C3 and C4 sites led to better performance in rifle shooting in an experimental group compared to a control group (Rostami et al., 2012). Additionally, increasing SMR (12–15 Hz) at Cz exhibited a significant enhancement in golf putting performance in the experimental group compared to a control group (Cheng et al., 2015). A mixed biofeedback protocol including increasing SMR (13–15 Hz) and inhibiting Theta (4–7 Hz) at Cz and T3 sites, together with heart rate variability (HRV) biofeedback in an uncontrolled study in gymnastics also showed a positive effect on balance (Shaw et al., 2012b). But again, increasing SMR (12–15 Hz) and inhibiting high Beta (22–26 Hz) and Theta (4–7 Hz) at the Cz site did not lead to significant effects on archery performance in the experimental group (Paul et al., 2011).

Although Paul et al. (2011) did not find a significant effect of increasing SMR on archers' performance, their study showed a significant effect on psychological status, that is, pre- and post-competition arousal level and pre-competition pleasure level were lower in the experimental group than in a control group (Paul et al., 2011). As mentioned above, in a group of swimmers, increasing SMR (12–15 Hz) and inhibiting Beta (22–37 Hz) and Theta (4–8 Hz) at C3 and C4 sites also led to reduced anxiety in the experimental group compared to a control group (Faridnia et al., 2012). In a sample of athletes from various sports, increasing SMR (12–15 Hz) concomitant with inhibiting Theta (4–7 Hz) and high Beta (21–35 Hz) at C3 and C4 in the experimental group led to significant changes in the levels of autotelic engagement and mental arithmetic performance compared to a control group (Mikicin, 2015).

3.1.3. **Alpha band**

Six of 14 studies applied NFT in the Alpha band, two including performance as an outcome variable. Again, crossover training (change from one protocol to another one) consisting of increasing Alpha (8–12 Hz) and Theta (4–8 Hz) and inhibiting high Beta (20–30

Hz) at the Pz site in rifle shooting led to better performance in the experimental group compared to a control group (Rostami et al., 2012).

Inhibiting high Alpha (10–12 Hz) and Theta (4–8 Hz) activity at the Fz site in golfers, however, failed to enhance performance in the experimental group compared to a control group (Ring et al., 2015). Also, inhibiting Alpha (8–11 Hz) while increasing Theta (5–8 Hz) at Pz failed to show a positive NFT effect on dance performance (Gruzelier et al., 2014b). However, a previous study in dance that had applied a similar protocol, that is, inhibiting Alpha while increasing Theta (based on IAF bands) at Pz showed better performance in the experimental group (Raymond et al., 2005).

Increasing individual Alpha frequency band (IAF ± 2 Hz) at C3 and C4 sites in gymnasts failed to show significant changes in mood (stress and arousal) and training experiences (perceived training sessions). However, two scales of the questionnaire that surveyed "being in shape" showed significant improvement in the experimental group as compared to a control group (Dekker et al., 2014).

A mixed protocol consisting of increasing Alpha at C3 and C4 sites, together with HRV biofeedback training in a single-subject study in track and field, led to better reaction (faster in reaction than the norm) in a GO/NOGO reaction time task (Ziółkowski et al., 2012).

3.1.4. **Theta band**

Three of 14 studies applied NFT in the Theta band, and all assessed performance as an outcome. As presented above, increasing Theta and inhibiting Alpha (frequencies based on IAF bands) at Pz in dance showed better performance in the experimental group compared to a control group (Raymond et al., 2005). However, a recent study in dance, applying a similar protocol (increasing Theta [5–8 Hz] and inhibiting Alpha [8–11 Hz] at Pz) failed to show a positive effect of NFT on performance (Gruzelier et al., 2014b). Inhibiting Theta activity (4–8 Hz) at Fz site in a single subject and a one-session study in golf resulted in better putting performance (Kao et al., 2014).

However, the same study failed to show significant effects of reduction or regulation of anxiety and confidence (Kao et al., 2014). Similarly, increasing Theta (5–8 Hz) and inhibiting Alpha (8–11 Hz) at Pz site failed to affect measures of dancers' depression, anxiety, and stress (Gruzelier et al., 2014b). Even so, this study provided evidence for increased creativity elaboration in the experimental group compared to a control group (Gruzelier et al., 2014b).

3.1.5. Slow cortical potential protocols (SCP)

Only the seminal study by Landers et al. (1991) applied SCP. Archers received a single-session SCP intervention, and participants were divided into two experimental groups that received feedback from either the T3 or T4 site. Participants who received feedback from the T3 site (right) showed a positive effect on archery performance (Landers et al., 1991).

3.1.6. Personalized event-locked EEG-profile

Among the 14 studies, one non-control study design retrieved an applied personalized event-locked EEG profile for NFT at the FPz site, showing a positive effect of training on performance in golf (Arns et al., 2008).

3.1.7. Potential moderators

Studies' results were also scrutinized with respect to potential moderators' influence. These moderators included athletes' gender and their level of expertise. Table 2 demonstrates the conclusion that no clear association exists between the two moderators and outcomes. No study directly compared either of the moderators.

3.1.8. Practical reports

As section 2.2 reported, 12 of 26 studies initially included were found to report incomplete information on their methods and therefore excluded from further analysis. All of these 12 studies presented results from practical interventions which are presented here for reasons of providing a more comprehensive overview. NFT was reported to improve sport performance in soccer players (Wilson et al., 2006), short-track speed skaters (Beauchamp et al., 2012), gymnasts (Shaw et al., 2012a), golfers (Sherlin et al., 2015) and in a tennis player (Gracz et al., 2007) and a rifle shooter (Harkness, 2009). Affective outcome were also reported to be enhanced after NFT with a dancer (Singer, 2004), a skier (Pop-Jordanova and Demerdzieva, 2010), a track and field athlete (Todd, 2011), winter Olympic athletes (Dupee and Werthner, 2011), short-track speed skaters (Beauchamp et al., 2012) and baseball players (Sherlin et al., 2013) and also a canoe athlete (Christie and Werthner, 2015). The most striking observation to emerge from the data in this part is that not any negative or non-improvements were reported in the practical reports.

3.2. Discussion, conclusion and answer to the first question

Regarding the NFT's effectiveness in sports, results show that 12 of 14 full studies reported positive effects for athletes. Seven of 10 studies (with at least one performance variable) showed positive effects on performance. Also, three of six studies assessing affective variables showed NFT's positive effect on affective outcome. Finally, three of three studies showed positive effects on cognitive outcomes.

Although Table 2 does not indicate moderators' effects, and moderators' levels were not directly compared in any of these studies, there are indications for moderating effects of the level of athletes' expertise, the frequency range and the form of performance evaluation. Whereas for pre-elite and elite athletes in archery and rifle shooting positive effects of NFT were found (Landers et al., 1991; Rostami et al., 2012) university-level athletes failed to show improvements in archery performance (Paul et al., 2011). Studies also differ with respect to defining the range of the selected frequency band. For example, Paul et al. (2011) defined the SMR band more liberally (i.e. 12 to 15 Hz) and failed to show a positive effect on performance of archers, whereas Rostami et al. (2012) defined the SMR band more narrowly (i.e., 13 to 15 Hz) and found a positive effect on the performance of rifle shooters. A systematic analysis of bandwidth choice for NFT performance is not yet available in the literature, but would be a desirable aim of future research. Regarding the moderating effects of performance evaluation, two studies used a similar NFT protocol in the Theta/Alpha ratio band but found differing effects on dance performance. Raymond et al. (2005) showed significant positive effects on performance. However, Gruzelier et al. (2014) failed to show significant effects of NFT on dancers' performance and argued that the restricted time for assessment of dance performance in their study may have led to differences.

The main goal of the current review was to determine the effectiveness of NFT on athletes' performance. At first glimpse, results suggest a role for NFT in optimizing performance and also in affective and cognitive variables indirectly related to performance. This impression from analyzing the full studies is echoed by the reports from practical intervention studies and corroborates conclusions in previous, more general reviews (Gruzelier, 2014a). However, after closer inspection of the data, we cannot easily infer or conclude that NFT is useful for improving athletes' performance and/or relevant underlying aspects of cognition and affect. This is due to the following. First, the data shows disagreement between protocols and outcomes. For instance, similar results have been obtained in the same discipline through different protocols (e.g., in golf, increasing SMR or suppressing Theta led to better performance). Likewise, different results in the same discipline have been obtained through the same or similar protocols (e.g., in dance, the Alpha/Theta protocol led to contradicting results in two different studies). A second source of uncertainty is the data's validity. To this end, we need to examine results for this review's second question.

4. Evaluation of empirical studies

To evaluate the quality of evidence for NFT's effectiveness in sport, we need to define criteria against which studies can be scrutinized. We firstly (1) followed the criteria laid out in the most recent, but more general review by Gruzelier (2014a, 2014c) that refer to the protocol's specificity with respect to frequency and site (Gruzelier, 2014c; Hammond, 2011). In addition, we considered as further cardinal criteria (2) the type of feedback (Vernon, 2005) and (3) the number of training sessions (Hammond, 2011). In addition to these previously used cardinal criteria, (4) more general methodological criteria also apply.

4.1. Criteria for evaluation

4.1.1. Specificity of frequency and site of recording

Gruzelier (2014c) and Hammond (2011) indicate that frequency selection for NFT and site of recording selection are two cardinal aspects of an NFT protocol. The rationale for selection of a frequency band should be theoretically and empirically established associations between the EEG's specific frequency band and a particular behavioral, affective, or cognitive outcome. If such an association is established, the idea for applying NFT lies in changing, that is, strengthening or inhibiting, the relevant EEG frequency band to improve the outcome. A sound theoretical and empirical association is important for two reasons. First of all, only if a positive association between the frequency band and the target outcome exists, can one expect any positive NFT effects in the respective band. Secondly, applying NFT can have adverse effects; thus also for ethical concerns, positive association between a frequency band and some target variable needs to be established. An early study with patients with ADD and ADHD highlights that the disorder's symptoms could either be improved with neurofeedback or aggravated through similar NFT. In an A-B-A reversal design, Lubar and Shouse (1976) found that when Theta (4–7 Hz) was inhibited and the sensorimotor rhythm reinforced, ADHD symptoms improved. However, when Theta was reinforced, there was deterioration and reversal of positive improvements (Hammond and Kirk, 2007).

In line with specifying the frequency, the site of EEG-recording also has to be specified—based on an established association between the specific frequency at that site and a target outcome. The seminal study by Landers et al. (1991) is a good example for the importance of choosing the correct site. The participants' task was to increase slow cortical potentials either in the left hemisphere (T3, "correct-feedback") or in the right (T4, "incorrect feedback"). As expected, significantly improved archery performance was found only in the correct feedback group, whereas the incorrect feedback group showed a significant performance decrement from pre- to post-test.

Notably, the rationale for selecting the specificity of frequency and recording site can be provided at different levels of task specificity. Selection can be based on neurophysiological and psychological evidence directly derived from previous examinations of associations between brain patterns and outcomes in the specific task. For example, in the seminal study by Landers et al. (1991), first, an association between lower left temporal activation and optimal performance in archery was established. Then, archers received NFT to decrease left temporal activation to improve performance in this specific task. But the rationale can also come more indirectly from established associations between brain patterns and outcomes in similar tasks or outcomes in more general task requirements (e.g., "concentration"). For example, Cheng et al. (2015) decided to increase SMR to improve golf putting not based on previous analysis of the golf putt, but because "SMR NFT has a beneficial effect on attention-related performance in various attentional tasks" (p. 627). Finally, a rationale for selection of a specific protocol may not be provided at all or simply be related to general evidence (e.g., known effects of NFT on performance enhancement).

4.1.2. Type of Feedback

For the feedback loop to function properly, it is essential that the type of feedback presentation be chosen carefully, that is, it is necessary to consider how and through which sensory modality the information related to the frequency band should be fed back to the individual. Evidence from general psychology indicates that people respond more efficiently to a target presented in more than one modality (Giray and Ulrich, 1993). In line with such general findings, it has been found that, for example, blood pressure can be more effectively lowered using combined audiovisual feedback than using simple audio feedback (Lal et al., 1998). Furthermore, the review by Vernon et al. (2004) shows that most studies that applied NFT for treating ADHD have used audiovisual feedback. Vernon et al. (2004) suggested that providing both auditory and visual feedback may be a more efficacious method for informing the participant of his/her psychophysiological state. For instance, even though attention to one signal wanders, the remaining signal can redirect attention to the task (Vernon et al., 2004).

4.1.3. Number of sessions

As in any type of training, the amount of training is crucial in determining its effectiveness. Although temporary and transient changes in the EEG occur after only one NFT session (Vernon et al., 2003), further sessions are commonly needed to reveal more prolonged effects. Konareva (2005) assumed that successful NFT regulation may require a minimum of three to four sessions. He argued that the trainee becomes accustomed to the equipment, setting, and training regime during this period (Konareva, 2005). This view is supported by Hammond (2011) who believes that initial improvements can be noticed only within the first five to ten sessions. Gruzelier et al. (2006) similarly argued that NFT benefits could be seen only after 10 training sessions and mentioned that clinical samples would require longer training (Gruzelier et al., 2006). Furthermore, a large number of intervention sessions have been shown to be effective from the finding that an NFT intervention of 40 intervention sessions caused microstructural changes in the brain's white and gray matter (Ghaziri et al., 2013).

4.1.4. General methodological criteria

Evidence-based interventions rely on sound experimental evaluation studies that generally consider the population from which the sample is drawn, random selection and sample size, control group design, and random assignment to groups. Thus, if a study intends to provide evidence for NFT's effectiveness in elite sports, the sample must be generated from a population of elite athletes. Furthermore, the sample should be drawn randomly, comprising members of more than one team, for example. When using a standard intervention design that involves two points of measurement and two groups, to find medium effect size, the sample should consist of a minimum of 17 persons per group (based on a priori sample size calculation using G*Power with $\alpha = 0.05$, $\beta = 0.80$, Faul et al., 2007). As is true with most therapeutic modalities, NFT's effect is largely influenced by what patients expect, that is, the placebo effect (Hammond, 2011). Thus, to disentangle such confounders from true intervention effects, not only a control, but also a placebo group is paramount.

4.2. Evaluation and discussion with regard to criteria

This review's second question addressed whether evidence for NFT's effectiveness still holds when studies are tested against cardinal criteria, specifically related to NFT, and methodological criteria.

Regarding the cardinal criterion of specificity (of frequency and site), selecting a protocol based on direct association of outcomes in a specific task with brain patterns may be regarded as a "gold standard." Four of 14 studies followed this gold standard and chose their protocol(s) based on a direct rationale—among them the study by Landers et al. (1991). Most (n = 7) studies applied protocols based on findings that they were successfully applied in studies outside sports or in other sports disciplines. Furthermore, three studies failed to provide a clear rationale for selected protocols. Obviously, only a few studies have been concerned with the protocol's specificity, at least with respect to providing enough and direct evidence for the selection. However—considering that mobility in most sports still limits EEG assessment (movement artifacts)—the gold standard may be simply beyond reach for many sports tasks. From an inspection of Table 2, the protocol's rationale does not seem to have great influence on NFT's effectiveness. Still, given the lack of direct rationales, studies investigating NFT's effectiveness in sports tasks should take great care in deriving and transferring NFT protocols from other disciplines or domains.

The second cardinal criterion refers to type of feedback. Only four of 14 studies simultaneously used visual and auditory feedback, and no study directly compared the effectiveness of unimodal or bimodal feedback. Table 2 makes it apparent that most studies used audio feedback alone, much less combined audiovisual feedback. This is in contrast to clinical studies, for example, in ADHD, for which Vernon et al. (2004) indicated that the majority used a combination of visual and auditory feedback. Although it has been argued that combined audio and visual feedback may increase effectiveness (Vernon, 2005), actual effectiveness may depend on the task. If NFT is to become better integrated into field applications, the feedback type needs to fit task demands. For instance, when golfers receive NFT during preparation for and execution of a golf swing, audio feedback appears more suitable to the task than visual or audiovisual feedback (see Ring et al., 2015).

The third cardinal criterion refers to the number of intervention sessions. More than half the studies (nine of 14) were conducted with five or more intervention sessions. Studies thus often follow recommendations for prolonged intervention periods. However, no relation to NFT's effectiveness is apparent from Table 2, and no study directly compared the effectiveness of different training schedules. Nevertheless, length of training may be related to purpose of training. For example, studies show that for treating anxiety or insomnia, only 15 to 20 sessions may be necessary, while for other conditions, such as ADD or ADHD, 30 to 50 sessions may be required (Hammond, 2011). So far, however, there has been little discussion about the number of sessions for athletes and even less regarding different levels of sports expertise or disciplines. Wilson and Peper (2011) believe that athletes may benefit more from biofeedback in general than non-athletes. Athletes are highly motivated to succeed and to do what is necessary to improve performance. Likewise, interaction with the feedback process is much easier for athletes because they experience various types of feedback during training and practice anyway. They also spend most of their lives looking for and believing in measures that deliver success.

The last, but not least, criteria refer to methodological issues that include population, random selection of sample, and sample size. Of the 14 studies reviewed, 12 suffer from small sample size. As mentioned above with regard to medium effect size, the sample should consist of a minimum of 17 persons per group; however, the participant range in most studies was one to 13 (except Gruzelier et al., 2014b; Mikicin, 2015). In addition, 10 of 14 studies used an evaluation design consisting of a pre- and post-intervention measurement in different groups. Of these 10 studies, four included a placebo control group. The study by Ring et al. (2015) is an example that emphasizes the importance of a control group. They reported that, although participants in the intervention group learned to reduce their frontal high-Alpha power before putts (an expert-like pattern), the training regime failed selectively to enhance performance, as both the intervention and control groups improved putting performance to the same degree.

Moreover, seven of eight studies randomly assigned their participants (Dekker et al., 2014; Mikicin, 2015 did not report about group allocation).

The overview of empirical studies investigating NFT's effectiveness in sports revealed that 12 studies showed positive effects in general. More specifically, of the 10 studies that investigated effects on athletic performance, seven showed positive effects. The second question's purpose was to scrutinize this evidence for effectiveness with respect to criteria. Three of seven studies related to performance reported a direct rationale, and no study of five related to affective or cognitive outcomes reported a direct rationale. Two of seven studies related to performance reported bimodal feedback, and two of five studies related to affective or cognitive outcomes reported bimodal feedback. Four of seven studies related to performance reported more than five sessions, and four of five studies related to affective or cognitive outcomes reported more than five sessions. Four of seven studies related to performance used a full evaluation design, and four of five studies related to affective or cognitive outcomes used a full evaluation design.

No study met the criteria on all four levels, and only three studies—Paul et al. (2011) in archery, Rostami et al. (2012) in rifle shooting, and Mikicin (2015) in athletics satisfied three levels: bimodal feedback, more than five intervention sessions, and a full evaluation design. Thus, although most studies show positive NFT effects in sports, the studies' quality of design may not allow a completely positive picture.

Regarding studies that did not provide initial evidence for effectiveness (three studies assessing performance and three studies assessing affective and cognitive outcomes), only one study (except Gruzelier et al., 2014b) collected data from an adequate sample size. This indicates that, with larger sample sizes, medium or smaller effects may eventually be detected.

5. General Discussion and Recommendations

Neurofeedback training (NFT) has been recognized as a method to enhance self-regulation. Recent reviews show NFT's effectiveness in ameliorating symptoms in clinical samples and in enhancing performance in non-clinical samples, for example musicians (Gruzelier, 2014a, b). Sport is an area that could very much profit from employing NFT. However, reviews regarding NFT application in sports, that is, assessing its effectiveness in enhancing sports performance, are lacking. Thus, the current review's main goal was to determine NFT's effectiveness on athletes' performance. To this end, we first presented an overview of empirical studies examining NFT's effects in sports and then evaluated the studies against cardinal and methodological criteria.

Our review indicates that, so far, the majority of published studies supports that NFT effectively improves athletes' performance in a specific sports task and/or in relevant underlying aspects of cognition and affect. Various protocols have been tested and have resulted in principally positive effects. This finding is in line with the conclusions drawn by Gruzelier (2014a, b) for other fields of applications. On closer inspection, however, evidence for specific protocols' effectiveness in enhancing sports performance is rather weak, this final conclusion taking the validity of the studies into account is quite different from the positive conclusions drawn by Gruzelier (2014a, b). First of all, in some instances, the same protocol had different effects within the same or a similar task; in another instance, different protocols led to similar effects within a sport. Secondly, the studies' quality appears to be non-optimal. No study satisfies all cardinal and methodological criteria that this review puts forward, and only a few satisfy most criteria. Thus, despite some indications that NFT use is effective for improving sports performance, substantial evidence for its effectiveness is missing.

The review also shows that developing NFT interventions in an applied setting is premature because evidence is very weak for specific interventions that rely on associations between training a specific frequency band and a performance measure. These results also highlight that notwithstanding early recognition of NFT's potential utility in sports (by Landers et al., 1991), application of NFT to optimize athletes' performance is still in its infancy. Therefore, this would be a fruitful area for further work, but for NF studies to advance, researchers need to address criteria that have raised questions about protocols' validity. Thus, there is a definite need for studies with larger sample sizes (see Schweizer and Furley, 2016, for a general discussion). Studies should also apply at least five intervention sessions because evidence seems to suggest five as the minimum number to accustom a trainee to the training regime and conditions. However, regarding NFT schedule, still, two other questions remain. First, how long should each training session last, and second, how training session should be spaced over time? It has been argued that training sessions should not be too long or too short. A long session makes participants exhausted and drowsy, on the other hand, change requires some time. In general, however, data from several sources have shown training with a duration of 20 to 30 minutes leads to success (e.g., see Ghaziri et al., 2013; Raymond et al., 2005; Rostami et al., 2012). With regard to spacing, empirical data are inconclusive but suggest longer spacing. From the general application of NFT, some studies that applied a massed training sessions in one day failed to show success (Albert et al., 1974; Nan et al., 2015). Vernon et al. (2009) pointed out that similar to other types of learning, spacing training over a period of days and/or weeks should be more effective than training massed within a single day (see Vernon et al., 2009, for more detail). For future studies, a greater focus on the rationale of the protocols (regarding the specificity of frequency and site) is also required. A plausible rationale for a protocol definitely needs to address task demands. In addition, the type of feedback needs to be matched with the intervention aim and design of the study.

In line with these issues, an aim of the current review was to provide a number of recommendations that future researchers should adopt for sports performance. Further recommendations are as follows: 1) Concerning ethical issues related to a placebo group, we suggest using a sham feedback intervention that lasts only one or two sessions. It is highly unfair, if not unethical, for participants to invest considerable time and effort to improve their performance but receive only sham feedback that is not expected to be effective in the first place. One strategy for dealing with this difficulty is to offer placebo-group participants the opportunity to receive the real intervention afterwards, once it has been proven effective and secure. However, it seems that participants are not interested in receiving the NFT option at a later time (La Vaque and Rossiter, 2001). 2) Studies so far have not been providing (much) evidence for changes in the trained frequency bands within sessions and across training. However, such information is important for evaluating why some interventions may have failed or produced only small effects (Gruzelier et al., 2014b). Thus frequency bands should not only be monitored for NFT but also recorded for later analyses. 3) As Cheng et al. (2015) have claimed, neurophysiological changes occur not only in trained frequencies at selected sites, but also in adjacent frequencies and sites. Thus EEG- monitoring and recordings for later analyses should apply a denser electrode layout. 4) It is doubtless that high-quality learning also requires genuine motivation. Thus, maintaining participants' motivation and compliance across the long and many intervention sessions in NFT is paramount. This matter can be reached through different ways e.g., a training protocol that after some sessions, provides to participants a feedback in the shape of a new audio- and/or visual stimulus. Furthermore, it is better to use more engaging feedback environments rather than boring and basic feedbacks such as a classic bar. A feedback should be inherently motivating and relevant for the learner and have an appeal of novelty, challenge, real-world relevance or aesthetic value. Game-like, 3D or virtual reality feedback has been found to be more effective compared to simple feedback such as a classic bar (Friedrich et al., 2015). 5) A general problem with NFT is that the competence to voluntarily change brain patterns needs to be transferred from a training environment to the playing field, which may include actual competitions (Vernon, 2005). Thus, it is important to design an intervention that integrates the NFT into the actual sport task (see for example the study by Ring et al., 2015).

The current review also gives insights to the direction for future research. It is clear that the number of NFT sessions and their duration requires more research that takes into account that athletes may differ from other populations and also considers the individual level of expertise. For instance, an expert is more experienced than a non-expert in terms of intensive transfer of skills learned in practice to application in competition, thus requiring fewer intervention sessions. Furthermore, studies so far have investigated closed skills such as golf and archery, thus for a more comprehensive understanding of the effectiveness of NFT in sport, more research needs to be done with open skills such as soccer and basketball.

In the real world of sport most behavior occurs in motion, in a behavioral stream that has ambiguous start signals and unpredictable conditions that is not directly comparable with conditions in the laboratory (Walsh, 2014). Thus the last, but definitely not the least, point to be considered in future research is expanding study conditions from the laboratory to the field, including actual performance situations. This transfer or expansion has two aspects: The first is related directly to research that needs to prove that its findings in the laboratory have external or ecological validity. If the effectiveness of NFT for improving sport performance is to be tested, it needs to be tested by assessing outcomes directly related to performance in a competition, if not performance in a competition in the first place. Training as well as outcome assessment need to take place under more realistic field-like or on-field conditions.

The second aspect refers to how athletes may be aided in transferring the skills acquired through NFT, usually under laboratory (-like) conditions, to the real world of competition. The reported studies do not give much detail about this problem. However, future interventions and also studies testing these interventions could be guided by the Wingate 5-Step Approach (W5SA; Boris and Iris, 2014). The W5SA is designed to transfer in five steps self-regulation skills acquired and trained in the laboratory to the field conditions and settings of practice and competition. In the W5SA the first three steps (introduction to skills training, identification of feedback modality, and simulation of competition), are provided in the laboratory and the last two steps (transformation, realization) are provided in training/competition settings. Based on this method, an intervention in the field of NFT can be designed from a very general to specific phase. For instance, in a simulation phase, NFT could be applied while athletes are being made excited, e.g., by observing films from competitions, or while athletes are distracted (e.g. by applying noises from competitions). For further transfer, NFT could be restricted in time and duration to match demands of the sport discipline (e.g. matching a pre competition preparation phase). Finally, NFT could be integrated into regular practice or training routines (e.g. during warm-up).

Taken together, the final conclusion about the validity of the findings in this review study is quite different from the positive conclusions drawn by Gruzelier (2014a, b). More research efforts, therefore, need to be made in the field of sports to uncover constraints and specifications for NFT in sport.

Conflict of interest

None

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Tables

Table 1

EEG frequency bands associated with mental state. Table is adapted from Barlow et al. (2007), page 256 and Cheron et al. (2016).

Name	Frequency	Features
Gamma	Above 30 Hz	Gamma oscillations are associated with cognitive activity, e.g., intensely focused attention, and increase with stimulation intensity and amount of attention to stimulation. Gamma oscillations are also observed during working memory maintenance and assist the brain in processing and binding information from different areas of the brain. (Horschig et al., 2014).
Beta	15-30 Hz	Mid Beta (16-20 Hz) is related to active problem solving, intellectual activity, outward focus, and attention. More Beta is required when learning a task than once it has been mastered. High Beta (19-22 Hz) can also be observed during negative ruminating in some individuals (Barlow et al., 2007).
SMR*	12-15 Hz	SMR is associated with relaxed attentiveness, and decreased anxiety and impulsivity. It may also correlate with a decrease in involuntary motor activity (Barlow et al., 2007; Gruzelier et al., 2014a). Functional brain connectivity between motor areas and visual processing areas has been observed to

		decrease due to SMR activation, indicating reduced sensorimotor interference (Wang and Hsieh, 2013).
Alpha	8-12 Hz	Alpha, by adolescence, is the dominant rhythm in EEG and generally is associated with a state of relaxation and self-awareness. High Alpha activity can be observed in regions that are not involved in the current task (Horschig et al., 2014).
Theta	4-8 Hz	Depending on where in the brain Theta oscillations are observed, Theta can be associated with internal orientation, intuition, drowsy states or memory function. Posterior Theta **may** indicate low arousal, tiredness, and inattention (Gruzelier, 2014a). In contrast, Theta power increases over temporal sites during encoding, maintenance, and retrieval. Over frontal regions, Theta power increases proportionally with task demands (Horschig et al., 2014).
Delta	0.5-4 Hz	Delta is dominant during deep sleep and is associated with memory consolidation (Cheron et al., 2016). While, in wakefulness it is associated with learning disabilities, cognitive impairment, and brain injury. (Barlow et al., 2007; Hammond, 2011).

* Sensory motor rhythm

Table 2:

Characteristics, distribution, and results of sports studies on neurofeedback training

Criteria and moderators		Positive effect of NFT: Significant P	A	C	Non-significant P	A	C
With control/ placebo group(s)	>5 sessions	8, 2, 14	4, 6, 13	10, 13	4, 10	9, 10	
	<5 sessions	1			12		
Without control/ placebo group(s)	>5 sessions	7					
	<5 sessions	11, 3		5		11	
Rationale for protocols	Specific	11, 3, 1			12	11	
	General	7, 8, 2, 14	4, 6, 13	5, 10, 13	4, 10	9, 10	
Type of feedback	Audio & visual	11, 8	4, 13	13	4	11	
	Audio	7, 3, 2, 14		10	12, 10	9, 10	
	Visual	1	6	5			
Sex	Both genders	3, 8, 1, 2, 14	4, 13	10, 13	4, 10	9, 10	
	Male	11		5	12	11	
	Female	7	6				
Experience*	High	11, 1, 14		5		9, 11	
	Medium	8	6				

	Low	7, 3	4		4, 12		
Separate result of training for each variable		7 of 10	3 of 6	3 of 3	3 of 10	3 of 6	0

Note. The numbers in table 2 are related to following studies, ordered by year of publication: 1 Landers, 1991; 2 Raymond, 2005; 3 Arns, 2008; 4 Paul, 2011; 5 Ziółkowski, 2012; 6 Faridnia, 2012; 7 Shaw, 2012; 8 Rostami, 2012; 9 Dekker, 2014; 10 Gruzelier, 2014; 11 Kao, 2014; 12 Ring, 2015; 13 Mikicin, 2015; 14 Cheng, 2015.

*Studies 2, 10, and 13 did not mention participants' levels. P=performance outcome, C=cognitive outcome, and A=affective outcome.

Table 3:

Applied protocols of neurofeedback training and outcome of studies

Frequency	Golf				Archery				Rifle shooting				Track & field				Swimming				Gymnastics				Dance				Athletes			
	P		C&A		P		C&A		P		C&A		P		C&A		P		C&A		P		C&A		P		C&A		P		C&A	
	+	0	+	0	+	0	+	0	+	0	+	0	+	0	+	0	+	0	+	0	+	0	+	0	+	0	+	0	+	0	+	0
Beta						↓	↓		↓										•↕												•↕	
SMR	↑					↑	↑		↑										↑		↑										↑	
Alpha		↓							↑				↑											↑	↓	↓	↓	↓				
Theta	↓	↓		↓		↓	↓		↓										↓		↓				↑	↑	↑	↑			↓	
Other approaches	*1				*2																											
Electrode site(s)	Fz(11); FPz(3); Cz(14)	Fz		Fz	T3	Cz	Cz		C3-C4,Pz				C3-C4						C3-C4		Cz-T3			C3-C4	Pz	Pz	Pz	Pz			C3-C4	
No. of study	11-3-14	12		11	1	4	4		8				5						6		7			9	2	10	10	10			13	

Note. ↑= reinforcement and ↓= suppression. •↕ those studies simultaneously reinforce and suppress Beta waves in different bandwidths.*1Personalized event locked EEG profile, and *2 SCPs. P=performance outcome, C=cognitive outcome, and A=affective outcome. + = positive significant effect. 0 = no significant effect.

Table 4:

Overview of studies

Author/Year	Intervention(s)	Electrode(s) location(s)	Type of feedback	Length of intervention	Controlled conditions	Outcome measures	Level of athlete	Sport discipline
Landers – 1991	Regulation of slow cortical potential. Correct feedback (greater left hemisphere low frequency activity) and incorrect feedback (greater right hemisphere low frequency activity)	T3 and T4	Visual	One session (as many as needed to show shift)	With control group	Performance, concentration, and self confidence	Pre elite	Archery
Raymond – 2005	Alpha/Theta ratio (Inhibit Alpha 8.5-11.5 Hz/ increase Theta 4.5-11.5 Hz), frequency band were based on the IAF	Pz	Auditory	4 week (10 session), 20 min	With control group	Dance performance	Imperial College dance sport team (Latin dance and ballroom)	Dance
Arns – 2008	The element of cortical activity that was fed back to participants was partly customized	FPz	Auditory	3 session (over different days) consisting of four series of 80 putts from their PD50 in an ABAB design (no feedback–feedback–no feedback–feedback)	Without control group	Golf putting performance (majority were held indoors), EEG	Amateur	Golf
Paul – 2011	Increase SMR (12-15 Hz), meanwhile inhibiting the Theta (4-7 Hz) along with high Beta (22-26 Hz)	Cz	Audio-Visual	12 session(4 week, 3 times pre-week), each session 20 min	With control group	HR (during performance), pleasure-arousal level, precision, performance (through competition) and baseline assessments of EEG were taken. SMR/ Theta ratio and SMR epoch	University level	Archery
Ziółkowski - 2012	HRV biofeedback along with NFT (increase Alpha)	C3 and C4	Visual	2 session, each session 30 min (10 min HRV and 20 min NFT)	Without control group	ERPs, social, and cognitive behavior	World rank	Track and field (javelin)
Faridnia - 2012	At first phase increase SMR (12-15) and decrease Theta (4-8) and high Beta (22-37) and in	C3 and C4	Visual	12 session (4 week and 3 sessions pre week), 45 min	With control group	Sport competition anxiety (SCAT)	National level	Swimming

	the second phase increase Beta (15-18) and decrease high Beta							
Shaw - 2012	HRV biofeedback along with NFT (Training to increase HRV and SMR rhythm while inhibiting Theta was provided)	Cz and T3	Auditory	10 session, 15 min (5 week, 2 times pre-week)	Without control group	Balance beam performance (through competition) and EEG assessment at T3 and Cz sites	Division I university (varsity)	Gymnastic
Rostami - 2012	2 protocol 1) increasing SMR (13-15) while inhibiting high Beta (20-30) 2) increasing Alpha and Theta (8-12 & 4-8 crossover between them) while inhibiting high Beta	C3 and C4 for SMR and Pz for Alpha and Theta	Audio-visual	15 session (5 week,3 times pre-week), 60 min (30 min for each protocol)	With control group	Performance (shot result)	National and provincial	Rifle shooting
Dekker - 2014	Increasing Alpha in experimental group and random Beta in placebo group	C3 and C4	Auditory	10 session, each session consists of three periods of 8 min.	With control group	qEEG, and behavior after 2 month follow up measurement, and one week after that participated in a "simulated competition day"	Elite	Gymnastic
Gruzelier - 2014	Alpha/Theta ratio (Inhibit Alpha 8.5-11.5 Hz/ increase Theta 4.5-11.5 Hz), frequency band were based on the IAF	Pz	Auditory	10 sessions (twice a week, each session lasted for 20 min)	With control group	Dance performance, cognitive creativity, mood, presence in performance, personality	BA students at conservatoire of music and dance	Dance
Kao - 2014	Reducing frontal midline Theta (4-8) amplitude	Fz	Audio-visual	One session, approximately 25 min	Without control group	Golf putting performance (golf green simulator), EEG, Competitive state anxiety (CSAI-2)	Professional	Golf
Ring - 2015	Reduce Theta (4-8 Hz) and high-Alpha (10-12 Hz) power	Fz	Auditory	3 session, 1-h (twelve 5-min blocks of putts)	With control group	EEG and putting performance	Recreational golfers	Golf

						under both low and high pressure conditions		
Mikicin - 2015	Increase Beta1 (21-35) and SMR (12-15) meanwhile decrease Theta (4-7) and Beta2 (21-35)	C3 and C4	Audio and visual	20 sessions (4 months, every 7 days)	With control group	Autotelic engagement and work curve test	Student Athletes	Swimming, fencing, track and field, taekwondo, and judo
Cheng - 2015	Increase SMR (12-15)	Cz	Audio	8 sessions, lasting 5 weeks. Each session was composed of 30 to 45 min	With control group	Golf putt	Pre-elite and elite athletes	Golf