Neurofeedback training to optimize athletes' performance:

from overview to application

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Overview

That athletic performance is influenced by brain oscillatory activity, and distinct patterns of brain activity can indicate optimal and suboptimal performance is well established. A notable example is the relationship between brain oscillatory activity in the range of alpha (7 – 13 Hz) and targeting accuracy (e.g., in archery). A good performance here is associated with activation in the right hemisphere of the brain, which is associated with visual-spatial processing, and, simultaneously, decreased activation in the verbal-analytic area, located in the left temporal lobe, which is related to a reduction in attention to stimuli and suppression of irrelevant information. Empirical evidence suggests that brain stimulation techniques (such as neurofeedback training) can be utilized to change brain oscillations. Neurofeedback training (NFT) is the process by which an individual is presented with (approximately) real-time feedback of his own brain activity (or other parameters such as blood flow). While a participant is supposed to learn (consciously or not) strategies to alter these parameters to reach a level where he can more efficiently regulate them, aiming to treat some mental disorders or to optimize behaviors. Thus far, the effectiveness of NFT has been assessed with regard to its applications in clinical populations, as well as the enhancement of performance in a variety of contexts. However, evaluations of the effectiveness of NFT in the sports domain is lacking, although the use of NFT to optimize athletes' performance goes back to 1991, when it was first applied to improve targeting accuracy in archery.

In this dissertation, in the first step I investigate the effectiveness of NFT in the field of sport. Further, I evaluate the quality of empirical studies that address athletic performance by defining some methodological and theoretical criteria with which these studies can be scrutinized. Various protocols in a number of sport disciplines were examined, which demonstrated the positive effects of NFT in 12 of 14 studies. However, these studies also contained substantial methodological limitations.

In the second step, by applying the criteria from the first step (as part of the results of systematic review article), I designed and conducted an empirical study to explore the effects of NFT on attention and reaction time (RT) performance of athletes. No significant enhancement in selective attention, a reduction in RTs, and no changes in trained frequencies of the participants of any intervention groups were found when compared with the placebo/control group.

While the focus of the first two studies of this dissertation was mostly on the effect of NFT on athletes' performance and criteria that enabled the researchers evaluate the quality of the findings, in the third step (as a perspective article) the focus was on the psychophysiological framework and neural mechanism underlying NFT. I first identified the potential and challenges in research aiming to change brain function through closed-loop NFT. I introduced a novel allostasis-based model of NFT, which frames acquired changes in brain function as emergent processes resulting from adaptive self-regulatory processes. Then, I documented these processes at the micro and the macro levels. Finally, in this perspective article, I examined recent findings on neurophysiological structural and functional adaptations during NFT, which are then linked to the model presented in this article, and then I make predictions about mechanisms and outcomes of NFT.

In sum, this dissertation, after a comprehensive and critical review of the extant neurofeedback literature in the field of sport, has identified some encouraging evidence for NFT as an approach that should enhance sporting performance in some circumstances; however, this evidence is on shaky grounds and on the basis of current research the jury is most definitely still out. Moreover, when I tested the effectiveness of NFT on attention and RT of athletes in a well-controlled manner, the results showed a smaller effect than what was found in the literature. The final contribution of this dissertation highlights the current general debates on NFT and its effectiveness, and offers a solution by developing an allostasis four-stage model of NFT, in which I argue NFT augments the competence to more flexibly self-regulate brain states. By considering this new framework researchers and practitioners in the field of NFT will be able to provide a better rationale for their interventions. This framework, also, identifies boundaries for what changes can be expected from a neurofeedback intervention and propose a time frame for such changes.

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Dissertation structure

This dissertation consists of four chapters. Chapter 1 begins by laying out the importance of self-regulation, briefly looks at benefits of the feedback approach, a short introduction to NFT and its procedures, and presents the statement of the problem. In Chapter 2 I present the methodologies that were used in the articles. Chapter 3 consists of two publications and a submission: article 1) presents the findings of the systematic review of neurofeedback studies in the sport domain, focusing on two key themes; a) the effectiveness of neurofeedback training as measured in the outcomes, and b) the quality of studies when evaluated via general methodological and specific theoretical criteria. Article 2) is comprised of two empirical studies, the first of which is a pilot study for the second, which addresses the effect of NFT in the range of Beta Band components on attention and RTs Performance. Article 3) explains the neurophysiological mechanism underlying neurofeedback training, focusing on three key themes: a) the psycho-physiological framework of neurofeedback training, b) the empirical evidence regarding the neural mechanisms underlying neurofeedback training, and c) the expected effects of neurofeedback training on non-clinical vs. clinical applications. The last chapter draws a conclusion based on the previous chapters, highlights the questions that are still open, and outlines future directions to further explore the potential merits of neurofeedback training for optimizing athletes' performances.

Introduction

When we think of evolution, generally, we think of how physical characteristics evolved through natural selection and not about the role that evolutionary processes has played in the development of physiological and behavioral characteristics. However, several lines of evidence suggest that the hominid ancestors most likely to reproduce and pass along their genes were those whose physiological and behavioral characteristics were able to adapt to challenging conditions. Regulatory skills played an important role in assisting our ancestors to survive and even flourish when other hominid ancestors went extinct. Given that, it follows that one important quality as humans is our capability to self-regulate (Boekaerts, Pintrich, & Zeidner, 2005; Heatherton, 2011).

Self-regulation refers to the process of guiding one's own thoughts, behaviors, and feelings to reach certain goals. Such regulation consists of several stages, and individuals must function as contributors to their own motivation, behavior, and development within a network of reciprocally interacting influences (Cleary & Zimmerman, 2001). Physiological self-regulation, *as a subprocess of self-regulation*, is comprised of voluntary control over functions of the central nervous system (CNS) and the peripheral nervous system (PNS), the latter comprising the somatic nervous system (SNS) and the autonomic nervous system (ANS; J. H. Gruzelier & Egner, 2004).

The concept of physiological self-regulation has been widely used for radically different purposes, due to its capacity to modify behavior. For example, optimizing performance is one of the most common purposes for which physiological self-regulation has been applied. Generally speaking, a good performance is linked to a high degree of control over both mental and emotional processes; an individual must attain high levels of concentration when performing without becoming overly tense or excited. Today, such control is often acquired by means of instrumental learning, which refers to the adjustment of behavior in response to the behavior's perceived consequences. Thus, more research is needed on behavior modification through self-regulation.

Instrumental learning (operant conditioning)

As mentioned above, voluntary control over CNS and PNS functions can be acquired through instrumental learning, which is also referred to as operant conditioning. Our ancestors applied the principles of this type of conditioning once there were dogs to herd, horses to ride, and small children to toilet-train. However, the first serious discussions and analyses to explore how animals learn new behaviors emerged toward the end of the nineteenth century, when Ivan Pavlov was exploring the phenomenon of associative learning which later became known as classical conditioning, while Edward Thorndike was systematically exploring operant conditioning (Gluck, Mercado, & Myers, 2016). Operant conditioning, like classical conditioning, is one of the major types of associative learning; however, it differs substantially from classical conditioning in that it is dependent on voluntary actions performed by the participant (Hall & Stewart, 2010). In this type of learning, the probability that a behavior or response is learned and performed depends on whether that response is followed by a reward or punishment. The evidence of rewards, punishments, and knowledge of results can be clearly seen in the case of learning a new skill and/or optimizing it.

For example, when someone is improving voluntary control of their free throw in basketball, seeing the shot go through the basket (success) serves as a reward, and seeing it miss (failure) serves as a punishment. If a learner is blindfolded, so that he does not have any knowledge of the results of his shots, he would not learn. Rewards, punishments, and knowledge of results are collectively called feedback. Examinations of operant conditioning of ANS responses in animals have shown that, when accurate feedback is connected to reinforcement, animals can learn to control such autonomic measures as blood pressure and galvanic skin response (see

Kimmel, 1974). Furthermore, even when there is no control of voluntary muscular changes peripheral responses can be obtained (N. E. Miller & DiCara, 1967).

However, most people are poor at perceiving their own physiological responses, such as blood pressure, analogous to the blindfolded beginner trying to learn to shoot baskets. Advanced measuring equipment can "remove the blindfold" by supplying better feedback, which is given by a device that promptly measures a biological function; this is known as biofeedback. Nowadays, various types of neuro-physiological signals are used as feedback, e.g. the brain’s electrical activity. The brain’s electrical activity, measured by electroencephalography, is called EEG biofeedback or neurofeedback, when provided to the subject (N E Miller, 1978).

What is NFT and how does it work?

NFT, as a type of biofeedback training, is a conditioning technique that entails participants learning to control brain activity (Hashemian, Farrokhi, Mirifar, Keihani, & Sadjadi, 2013). The brain activity in an NFT intervention can be measured and fed back to a participant through the following approaches: a) functional magnetic resonance imaging (fMRI), b) magnetoencephalography (MEG), c) near-infrared spectroscopy (NIRS), and d) electroencephalography (EEG; Cooke, Bellomo, Gallicchio, & Ring, 2018; Thibault et al., 2015). The focus of this dissertation is on the latter approach, “EEG-NFT”, which is the most common way to conduct an NFT intervention (Hammond, 2011) and is perhaps more suitable in the field of sport (Hung & Cheng, 2018).

Table 1. Popularity, cost, and availability of neurofeedback modalities (taken from Thibault et al., 2015).

	EEG	fMRI	MEG	fNIRS
First application to neurofeedback	1958	2003	2005	2007
Number of practitioners worldwide	>1000	None	None	None
Number of research labs†	>50	~10	3	~5
Cost of initial set-up	$500 – 5,000 (Personal use) $5,000 – 50,000 (Research use)	$500,000 – 2M	$ 2M	$50,000 – 300,000
Running costs‡	No extra fees	~$500/hour	~$500/hour	No extra fees
Cost for patient§	$130-225/session $4,000 – 10,000/ complete regimen	Not available to patients	Not available to patients	Not available to patients
Marketed equipment	Many companies sell products for clinical, research, and personal uses	One software package for research use only	None (all labs run in-house software)	None (all labs run in-house software)

EEG, which is one of the most reliable tools (in its non-invasive manner using electrodes affixed to the scalp), records currents in the cerebral cortex that develop during synaptic excitations of the dendrites of pyramidal neurons (Sanei & Chambers, 2007). EEG studies have shown that our brain is never at rest and spontaneous brain oscillatory activities vary in frequency (Zagha & McCormick, 2014), which are measured in cycles per second or hertz (Hz). In the literature, brain (or neural) oscillations has come to be used as a term referring to the rhythmic and/or repetitive electrical fluctuations (activity) generated spontaneously and in response to stimuli by neural tissue in the CNS (Basar, 2013). The oscillatory activities are classically subdivided into five frequency bands, which range from slow to fast frequencies:

delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), gamma (> 30 Hz; see, e.g., Groppe et al., 2013). However, sometimes researchers subdivide them into minor frequencies (e.g., low alpha [8 – 10 Hz] and high alpha [10 – 12 Hz]). EEG studies have also revealed that these frequencies are associated with different mental and physical states.

Accordingly, the aim of EEG-NFT is to reinforce and/or inhibit fluctuations of these frequencies in order to stabilize a specific function of interest. The basic assumption of EEG-NFT practitioners is that changes in the band power of specific frequency ranges of the EEG leads to a change in a specific behavior (Vernon, 2005). Accordingly, the aim of EEG-NFT, in a training session, is to maintain the band power of a specific frequency within an optimal zone that has been associated with a desirable behavior by providing the audio and/or visual feedback in (approximately) real time. Further, in the out of lab condition (when the intervention is over and the competency of self-regulation has been developed), these practitioners expect a participant to enter and maintain the specific optimal zone without the assistance of an NFT device.

The basic requirements of an EEG-NFT setup are as follow: a) an EEG electrode (or sensor) to transmit brain activity; b) an amplifier that receives the signals from the electrode and amplifies them, so that the computer can analyze and display them. An amplifier connects both the electrode and the computer via either a cord or a wireless connection; c) software to allow a practitioner to select which elements of the EEG signal are fed back, also to allow the practitioner to set a desired condition (called a threshold) or goal to give feedback; and finally d) a computer with a screen and speakers to display the acquired signals in visual and/or auditory form. These components are illustrated in Figure 1.

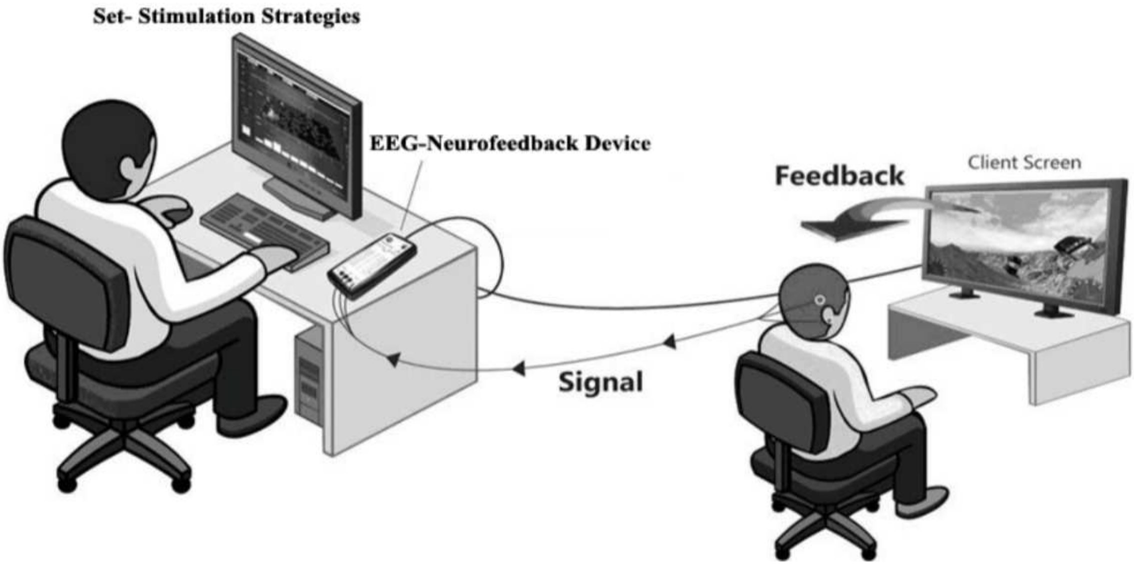

Figure 1. The procedure of the EEG-NFT (taken from Alhiyali et al., 2018)

As can be seen in Figure 1, in a non-invasive EEG-NFT session, practitioners seat participants, apply skin prep gel at recording site(s) to effectively lower the impedance, and then apply some conductive paste to attach electrodes to the scalp. Then, a simple auditory and/or visual cue is provided to participants to inform them either when their brain activity is in the desired direction (up or down) or is moving away from it. In such a setting, practitioners use operant conditioning to reward and/or punish specific brain activity and patterns to direct the function of the brain in the desired direction that is associated with a desirable behavior. Participants generally (in clinical applications) train for 30 - 60 minutes at a time and often return for up to 40 sessions (Cooke et al., 2018; Ghaziri & Thibault, 2019).

Potential applications of NFT

In the late 1960 researchers (see e.g., Kamiya, 1962; Wyrwicka & Sterman, 1968) demonstrated humans and animals, can acquire the ability to alter their EEG signals if given appropriate instructions and suitable feedback. Since then NFT has been applied, as an internal brain stimulation technique, to induce the ability to self-regulate (by up and down regulating) specific characteristics of the EEG. The effectiveness of NFT has, thus far, been investigated in various clinical and non-clinical applications: psychiatric (Fovet, Jardri, & Linden, 2015), autism (Kouijzer, de Moor, Gerrits, Buitelaar, & van Schie, 2009; Kouijzer, de Moor, Gerrits, Congedo, & van Schie, 2009), epilepsy (Strehl, Birkle, Worz, & Kotchoubey, 2014; Tan et al., 2009), stroke (Mihara et al., 2013; Wang, Mantini, & Gillebert, 2018), motor rehabilitation (Linden & Turner, 2016), insomnia (Cortoos, De Valck, Arns, Breteler, & Cluydts, 2010), learning-disabled children (Becerra et al., 2006), attention-deficit hyperactivity disorder (ADHD; Egner & Gruzelier, 2001; Gevensleben et al., 2010), tinnitus (Emmert et al., 2017; Guntensperger, Thuring, Meyer, Neff, & Kleinjung, 2017); improving cognitive performance (Zoefel, Huster, & Herrmann, 2011), enhancing working memory performance (Escolano, Aguilar, & Minguez, 2011) improving reaction times, spatial abilities, and creativity (Doppelmayr & Weber, 2011; Egner & Gruzelier, 2004); increasing the targeting accuracy in archery (Landers et al., 1991), increasing the targeting accuracy in gulf (Arns, Kleinnijenhuis, Fallahpour, & Breteler, 2008; Cheng et al., 2015).

Statement of the problem

Although, researchers have been using NFT for more than half century and studies have generally shown the promising effects of NFT, this approach has not escaped criticism from researchers. This dissertation focuses on two issues that are commonly debated: a) Whether NFT is effectively optimizes athletic performance. If so, to what extent is this evidence reliable? and b) From a more general perspective, how well can the current framework, on which NFT is based, explain the underlying mechanisms of NFT and the interaction between neurophysiological- and behavioral outcomes that are induced by NFT?

Historically, the first bio- and neuro-feedback approaches were limited to clinical medical practice in the 1960s. Since then, due to its practical applications, it has been extended to other disciplines. Researchers in sport science were attracted to biofeedback as early as the 1970s (Blumenstein & Orbach, 2014). Zeichkowsky (1975) was the first researcher to employ biofeedback training to learn about athletes' self-regulation. In this initial period, biofeedback studies focused on improving athletic performance by reducing state anxiety and muscle tension usually through galvanic skin response or electrodermal activity (GSR/EDA) and electromyography (EMG) feedback (e.g., French, 1978; Weinberg & Hunt, 1976; Zaichkowsky, 1983).

During the last few decades, the possibilities and potential of different types of biofeedback training to optimize athletes' performance have been examined in various reviews (e.g., Clarys & Cabri, 1993; Morgan & Mora, 2017; Petruzzello, Landers, & Salazar, 1991). However, the evaluation of the more recently developed type of biofeedback training, i.e. NFT, is lacking. As a result, for most practitioners the current state of knowledge on neurofeedback applications in sport is insufficient, regarding methodological factors (e.g. number and duration of training sessions), type of feedback (e.g. sensory modality), and protocols (e.g. the range of training frequency and site of the training). In addition, most studies in the field of NFT (specifically in the sports domain) have focused only on behavioral outcomes (e.g. more accurate targeting in pistol shooting), but not on the neurophysiological mechanisms underlying NFT, which some researchers have argued are necessary to understand and evaluate behavioral modifications. For instance, the evidence presented thus far has not clearly explained how much the neurophysiological changes induced by NFT differ between clinical and non-clinical applications.

With respect to the more general issues: First, the theoretical framework of NFT has come into question and concerns have been raised about whether the concept of homeostasis (which refers to regulatory processes that maintain the constancy of the physiology of organisms) is really suited for explaining how NFT tunes brain waves (e.g. Reiner, Gruzelier, Bamidis, & Auer, 2018). The second issue addresses the understanding of the neural mechanisms thought to underlie NFT. Although extensive research has shown positive behavioral outcomes resulting from NFT, this contrasts starkly to the fact that the neural mechanisms underlying

NFT – which likely comprise structural and functional plasticity across different levels of analysis – are still poorly understood. Partly reflecting this lack of understanding, several authors have also suggested that the effects of NFT like other medical interventions, may simply be due to placebo effects (Schabus, 2017; Thibault, Lifshitz, & Raz, 2016; Thibault & Raz, 2017). Thirdly, the lack of understanding of NFT's mechanisms on a model and a neural level has negatively impacted the understanding of the NFT process and subsequently the expectations about outcomes. For example, there is an on-going discussion among researchers about whether one should expect sustained changes in resting or baseline brain activity across sessions of an NFT intervention (see e.g. Schabus, 2018; Witte, Kober, & Wood, 2018).

Aims of the studies

This dissertation consists of three articles, which have been conducted in the following order: a) a systematic review with implications for future research, b) an empirical study, and c) a perspective article.

Historically, research in the field of NFT began by investigating the effects on clinical conditions, such as epilepsy and ADHD, and later its effectiveness was examined on healthy populations. The accumulated evidence suggest that NFT may enhance cognitive functions and behaviors in both clinical and healthy populations (J. H. Gruzelier, 2014; Rogala et al., 2016). However, no previous review has investigated the effectiveness of NFT in the sports domain. Meanwhile, there is increasing questions about the extent to which NFT can improve athletic performance. The aim of the first article was to investigate the effectiveness of NFT on athletic performance. It systematically reviews the neurofeedback studies in the field of sport, applying methodological and theoretical criteria to identify their strengths and weaknesses, and to provide clear guidelines for future research.

The existing body of research on EEG suggests that the Beta (13 – 30 Hz) frequency oscillations are associated with cognitive processing and faster reaction time (RT). The evidence in the field of NFT has also shown reinforcement of the brain oscillatory activity in the range of Beta improves cognitive processing capabilities and leads to faster RT. However, first, no previous study has investigated the effects of reinforcement of the Beta band in athletic RT. Second, the previous studies on a healthy non athletic papulation used different bands within the Beta frequency, making it difficult to compare studies. Thus, the aim of the second study was twofold. An empirical study is carried out, first, to apply the guidelines and recommendations generated in the review in order to assess the effect of NFT in a controlled manner. Second, after considering the importance of shortening the RTs in most sport disciplines, and the evidence of NFT's effectiveness in different Beta band components of healthy populations, I tested the effects of the NFT of Beta band components on the selective attention and various types of RTs' of athletes.

The theoretical framework of NFT has been questioned and concerns have been raised about whether the concept of homeostasis is suited for explaining how NFT tunes brain waves. Finally, the third paper in this dissertation develops a theoretical framework for NFT based on current understandings of psychophysiological regulation that in turn allows for a better understanding of the neurophysiological mechanisms of NFT: A novel allostasis-based model of NFT, which frames the newly-acquired changes in brain function as emergent processes resulting from adaptive self-regulatory processes. These processes can be documented across levels of observation, from the micro to the macro levels. Recent findings on neurophysiological structural and functional adaptations during and/or after NFT are then linked to this model, and I make predictions about mechanisms and outcomes of neurofeedback training.

Methodology

Thus far, the importance and objectives of the articles have been explained. The following section provides a detail overview of the methods used in each article.

Article 1: literature review and guidelines development

In Article 1, systematic review, PRISMA-methodology was used, as the preferred reporting items for systematic reviews and meta-analyses. The inclusion criteria were: a) original empirical, primary evidence/data, b) published in a peer-reviewed journal, and c) in English. A study was excluded if it lacks a complete report of the methods (especially the selected frequency and location of electrodes). Initially, 30 potentially relevant studies were examined, and then 14 were included. Studies were evaluated with respect to their outcomes and quality.

Article 2: Testing frequency specificity effects on RTs

Article 2 is an empirical investigation on 38 male soccer players with similar training backgrounds (a minimum of 90 minutes activity at least 4 times per week for a minimum duration of 4 years). After recruitment they were allocated to two intervention groups and one placebo/control group. First, a 3×2 ANOVA (group, time [initial pretest and second pretest]) with repeated measures on the latter was conducted for the validation analyses and methodological checks. Second, to identify the reliability of the dependent variables and potential training effects in sessions, a correlation analysis was conducted. Third, a 3 (groups) $\times$ 2 (time) ANOVA with a repeated time factor (second pretest and post-test) was conducted to investigate the effects of NFT group on simple and choice RT and the mean of the d2 test items. Fourth, a $2 \times 2 \times 2$ ANOVA (group, sessions [session 1 and session 10], and blocks [baseline before session and last block of session]) with repeated measures was conducted to examine the changes in the spectral power of the trained frequencies within and between sessions. Finally, a 3×2 ANOVA (group, time [second pretest and post-test]) with repeated measures was conducted to test the effects of NFT and placebo training on the spectral power of the trained frequencies during test performance (RT Task).

Article 3: Introducing a new perspective on the procedure underlying NFT mechanisms

Article 3 is a perspective paper, and instead of presenting research results, I commented on the current debates in the field of NFT. I first highlighted the current debate on whether the concept of homeostasis is suited for explaining how NFT tunes brain waves. I then developed a four-stage model of NFT based on allostasis, in which NFT optimizes the self-regulation of brain states. Furthermore, I reviewed research investigating the neural mechanisms underlying NFT – which comprise structural and functional plasticity across different levels of analysis – and linked these to the allostasis four-stage model. Moreover, the current understanding of neurophysiological structural and functional adaptations to NFT was linked to my allostasis four-stage model of NFT, and I derived predictions about mechanisms and outcomes of NFT. This linkage allowed addressing further theoretical issues, such as neural efficiency, which still have not been fully understood.

Publications and submissions

Article 1

Authors: Arash Mirifar, Jürgen Beckmann, & Felix Ehrlenspiel

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

Journal: Neuroscience & Biobehavioral Reviews

Doi: org/10.1016/j.neubiorev.2017.02.005

Summary:

The application of NFT to optimize athletic performance goes back to 1991 and interest in applying this approach is constantly-growing. This is evident in the case of some well-known examples, such as the famous Australian golfer *Jason Day* who reportedly uses NFT to learn more efficiently to get in the zone, or the members of the Italian soccer team who won the 2006 World Cup, and the Canadian short-track speed skating team who won five medals, including two golds, at the 2010 Vancouver Winter Olympic Games. Considering these examples, one could argue compellingly that NFT is a promising noninvasive approach to ensuring optimal performance of athletes, especially under high pressure conditions, where optimal performance matters most. This argument, however, would not be complete without a comprehensive and critical review of the extant sport neurofeedback literature. In doing so, this investigation examined the effects of NFT on athletic performance and evaluates these studies against NFT-specific and general methodological criteria. The results revealed some encouraging evidence for NFT that may optimize athletic performance in some circumstances; however, many studies' design quality do not allow a completely positive picture. This systematic review, also, offers some guidelines for future research, which should lead to more scientifically sound neurofeedback interventions to examine its potential to enhance athletic performance in the future.

The manuscript was submitted on the 18th of August 2016 and was accepted on the 5th of February 2017; from the 7th of February 2017 this article was available online and was published in April 2017 in Neuroscience & Biobehavioral Reviews, an international peer-reviewed journal. This journal "publishes review articles which are original and significant and deal with all aspects of neuroscience, where the relationship to the study of psychological processes and behavior is clearly established."

Contribution:

Arash Mirifar was the principal investigator and first author of the published article. He developed the idea for the systematic review and coordinated searching for and collecting the relevant studies from targeted databases. Arash Mirifar, also decided which studies to include based on inclusion and exclusion criteria, developed by Arash Mirifar and Felix Ehrlenspiel, and evaluated the studies included from different perspectives. Arash Mirifar wrote the paper. All co-authors reviewed and edited the manuscript.

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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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A B S T R A C T

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

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.

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 ($n = \mathbf{26}$) 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).

Table 2
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 et al. (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 et al. (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 et al. (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 et al. (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 et al. (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 et al. (2012)	At first phase increase SMR (12–15) and decrease Theta (4–8) and high Beta (22–37) and in the second phase increase Beta (15–18) and decrease high Beta	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
Shaw et al. (2012a,b)	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 et al. (2012)	1) 2 protocol 2) increasing SMR (13–15) while inhibiting high Beta (20–30) 3) 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 et al. (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 (2014a,b,c)	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 et al. (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 et al. (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 under both low and high pressure conditions	Recreational golfers	Golf
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 et al. (2015)	Increase SMR (12–15)	Cz	Audio	8 sessions, lasting 5 weeks. Each session was composed of 30–45 min	With control group	Golf putt	Pre-elite and elite athletes	Golf

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 3 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 3 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. 12–15 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., 13–15 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. (2014a,b) 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**, see** Table 4). 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,c) 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

Table 3
Characteristics, distribution, and results of sports studies on neurofeedback training.

Criteria and moderators		Positive effect of NFT					
		Significant			Non-significant		
		P	A	C	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 3 are related to following studies, ordered by year of publication: 1 Landers et al. (1991); 2 Raymond et al. (2005); 3 Arns et al. (2008); 4 Paul et al. (2011); 5 Ziółkowski et al. (2012); 6 Faridnia et al. (2012); 7 Shaw et al. (2012a,b); 8 Rostami et al. (2012); 9 Dekker et al. (2014); 10 Gruzelier (2014a,b,c); 11 Kao et al. (2014); 12 Ring et al. (2015); 13 Mikicin (2015); 14 Cheng et al. (2015).

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

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

Table 4
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.*1 Personalized event locked EEG profile, and *2 SCPs. P = performance outcome, C = cognitive outcome, and A = affective outcome. + = positive significant effect. 0 = no significant effect.

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 3, 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 3 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 3, 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 15–20 sessions may be necessary, while for other conditions, such as ADD or ADHD, 30–50 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 20–30 min 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.

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References

Albert, I.B., Simmons, J., Walker, J., 1974. Massed and spaced practice in alpha enhancement. Percept. Mot. Skills 39, 1039–1042.
Arns, M., Kleinnijenhuis, M., Fallahpour, K., Breteler, R., 2008. Golf performance enhancement and real-life neurofeedback training using personalized event-locked EEG profiles. J. Neurother. 11, 11–18.
Arns, M., de Ridder, S., Strehl, U., Breteler, M., Coenen, A., 2009. Efficacy of neurofeedback treatment in ADHD: the effects on inattention, impulsivity and hyperactivity: a meta-analysis. Clin. EEG Neurosci. 40, 180–189.
Barlow, D.H., Lehrer, P.M., Woolfolk, R.L., Sime, W.E., 2007. Principles and Practice of Stress Management. Guilford Press.
Beatty, J., Greenberg, A., Deibler, W.P., O'Hanlon, J.F., 1974. Operant control of occipital theta rhythm affects performance in a radar monitoring task. Science 183, 871–873.
Beauchamp, M.K., Harvey, R.H., Beauchamp, P.H., 2012. An integrated biofeedback and psychological skills training program for Canada's Olympic short-track speedskating team. J. Clin. Sport Psychol. 6, 67.
Becerra, J., Fernandez, T., Harmony, T., Caballero, M.I., Garcia, F., Fernandez-Bouzas, A., Santiago-Rodriguez, E., Prado-Alcala, R.A., 2006. Follow-up study of learning-disabled children treated with neurofeedback or placebo. Clin. EEG Neurosci. 37, 198–203.
Beckmann, J., Elbe, A.-M., 2015. Sport Psychological Interventions in Competitive Sports. Cambridge Scholars Publishing.
Boris, B., Iris, O., 2014. Biofeedback for Sport and Performance Enhancement. Oxford University Press.
Budzynski, T.H., Budzynski, H.K., Evans, J.R., Abarbanel, A., 2009. Introduction to Quantitative EEG and Neurofeedback: Advanced Theory and Applications, second edition. Academic Press.
Cashmore, E., 2008. Sport and Exercise Psychology: The Key Concepts. Routledge.
Cheng, M.Y., Huang, C.J., Chang, Y.K., Koester, D., Schack, T., Hung, T.M., 2015. Sensorimotor rhythm neurofeedback enhances golf putting performance. J. Sport Exerc. Psychol. 37, 626–636.
Cheron, G., Petit, G., Cheron, J., Leroy, A., Cebolla, A., Cevallos, C., Petieau, M., Hoellinger, T., Zarka, D., Clarinval, A.-M., 2016. Brain oscillations in sport: toward EEG biomarkers of performance. Front. Psychol. 7.
Christie, S., Werthner, P., 2015. Prestart psychophysiological profile of a 200-m canoe athlete: a comparison of best and worst reaction times. Biofeedback 43, 73–83.
Coben, R., Linden, M., Myers, T.E., 2010. Neurofeedback for autistic spectrum disorder: a review of the literature. Appl. Psychophysiol. Biofeedback 35, 83–105.
Dekker, M.K., Van den Berg, B.R., Denissen, A.J., Sitskoorn, M.M., Van Boxtel, G.J., 2014. Feasibility of eyes open alpha power training for mental enhancement in elite gymnasts. J. Sports Sci. 32, 1550–1560.

Del Percio, C., Rossini, P.M., Marzano, N., Iacoboni, M., Infarinato, F., Aschieri, P., Lino, A., Fiore, A., Toran, G., Babiloni, C., Eusebi, F., 2008. Is there a neural efficiency in athletes? A high-resolution EEG study. NeuroImage 42, 1544–1553.
Dupee, M., Werthner, P., 2011. Managing the stress response: the use of biofeedback and neurofeedback with Olympic athletes. Biofeedback 39, 92–94.
Egner, T., Gruzelier, J.H., 2004. EEG biofeedback of low beta band components: frequency-specific effects on variables of attention and event-related brain potentials. Clin. Neurophysiol. 115, 131–139.
Escolano, C., Aguilar, M., Minguez, J., 2011. EEG-based upper alpha neurofeedback training improves working memory performance, Engineering in medicine and biology society, EMBC. In: 2011 Annual International Conference of the IEEE. IEEE, pp. 2327–2330.
Faridnia, M., Shojaei, M., Rahimi, A., 2012. The effect of neurofeedback training on the anxiety of elite female swimmers. Ann. Biol. Res. 3, 1020–1028.
Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A., 2007. G* Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav. Res. Methods 39, 175–191.
Friedrich, E.V., Wood, G., Scherer, R., Neuper, C., 2015. Mind over Brain, Brain over Mind: Cognitive Causes and Consequences of Controlling Brain Activity. Frontiers Media SA.
Gevensleben, H., Holl, B., Albrecht, B., Schlamp, D., Kratz, O., Studer, P., Rothenberger, A., Moll, G.H., Heinrich, H., 2010. Neurofeedback training in children with ADHD: 6-month follow-up of a randomised controlled trial. Eur. Child Adolesc. Psychiatry 19, 715–724.
Ghaziri, J., Tucholka, A., Larue, V., Blanchette-Sylvestre, M., Reyburn, G., Gilbert, G., Levesque, J., Beauregard, M., 2013. Neurofeedback training induces changes in white and gray matter. Clin. EEG Neurosci. 44, 265–272.
Giray, M., Ulrich, R., 1993. Motor coactivation revealed by response force in divided and focused attention. J. Exp. Psychol. Hum. Percept. Perform. 19, 1278.
Gracz, J., Walczak, M., Wilinska, K., 2007. Seeking new methods of mental training in sport. Stud. Phys. Cult. Tour. 14, 97–102.
Gruzelier, J.H., Egner, T., 2004. Physiological self-regulation: biofeedback and neurofeedback. Musical Excellence, 197–219.
Gruzelier, J., Egner, T., Vernon, D., 2006. Validating the efficacy of neurofeedback for optimising performance. Prog. Brain Res. 159, 421–431.
Gruzelier, J., Foks, M., Steffert, T., Chen, M.-L., Ros, T., 2014a. Beneficial outcome from EEG-neurofeedback on creative music performance, attention and well-being in school children. Biol. Psychol. 95, 86–95.
Gruzelier, J., Thompson, T., Redding, E., Brandt, R., Steffert, T., 2014b. Application of alpha/theta neurofeedback and heart rate variability training to young contemporary dancers: state anxiety and creativity. Int. J. Psychophysiol. 93, 105–111.
Gruzelier, J.H., 2014a. EEG-neurofeedback for optimising performance. I: a review of cognitive and affective outcome in healthy participants. Neurosci. Biobehav. Rev. 44, 124–141.
Gruzelier, J.H., 2014b. EEG-neurofeedback for optimising performance. II: creativity, the performing arts and ecological validity. Neurosci. Biobehav. Rev. 44, 142–158.
Gruzelier, J.H., 2014c. EEG-neurofeedback for optimising performance. III: A review of methodological and theoretical considerations. Neurosci. Biobehav. Rev. 44, 159–182.
Hammond, D.C., Kirk, L., 2007. Negative effects and the need for standards of practice in neurofeedback. Biofeedback 35.
Hammond, D.C., 2011. What is neurofeedback: an update. J. Neurother. 15, 305–336.
Harkness, T., 2009. Psykinetics and biofeedback: Abhinav Bindra wins India's first-ever individual gold medal in Beijing Olympics. Biofeedback 37, 48–52.
Hatfield, B.D., Landers, D.M., Ray, W.J., 1984. Cognitive processes during self-paced motor performance: an electroencephalographic profile of skilled marksmen. J. Sport Psychol. 6, 42–59.
Horschig, J.M., Zumer, J.M., Bahramisharif, A., 2014. Hypothesis-driven methods to augment human cognition by optimizing cortical oscillations. Front. Syst. Neurosci. 8.
Iwadate, M., Mori, A., Ashizuka, T., Takayose, M., Ozawa, T., 2005. Long-term physical exercise and somatosensory event-related potentials. Exp. Brain Res. 160, 528–532.
Kamiya, J., 1962. Conditioned Discrimination of the EEG Alpha Rhythm in Humans. the Western Psychological, San Francisco, California.
Kao, S.-C., Huang, C.-J., Hung, T.-M., 2014. Neurofeedback training reduces frontal midline theta and improves putting performance in expert golfers. J. Appl. Sport Psychol. 26, 271–286.
Klimesch, W., 1999. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Res. Rev. 29, 169–195.
Konareva, I., 2005. Modifications of the EEG frequency pattern in humans related to a single neurofeedback session. Neurophysiology 37, 388–395.
Kouijzer, M.E., de Moor, J.M., Gerrits, B.J., Buitelaar, J.K., van Schie, H.T., 2009. Long-term effects of neurofeedback treatment in autism. Res. Autism Spectr. Disord. 3, 496–501.
La Vaque, T.J., Rossiter, T., 2001. The ethical use of placebo controls in clinical research: the Declaration of Helsinki. Appl. Psychophysiol. Biofeedback 26, 23–37.
Lal, S.K., Henderson, R.J., Carter, N., Bath, A., Hart, M.G., Langeluddecke, P., Hunyor, S.N., 1998. Effect of feedback signal and psychological characteristics on blood pressure self-manipulation capability. Psychophysiology 35, 405–412.
Landers, D.M., Petruzzello, S.J., Salazar, W., Crews, D.J., Kubitz, K.A., Gannon, T.L., Han, M., 1991. The influence of electrocortical biofeedback on performance in pre-elite archers. Med. Sci. Sports Exerc. 23, 123–129.
Larsen, S., Sherlin, L., 2013. Neurofeedback: an emerging technology for treating central nervous system dysregulation. Psychiatr. Clin. N. Am. 36, 163–168.
Lawrence, J., 2002. Neurofeedback and Your Brain: A Beginner's Manual. Faculty, NYU medical center & brain research lab, New York.
Lubar, J.F., Shouse, M.N., 1976. EEG and behavioral changes in a hyperkinetic child concurrent with training of the sensorimotor rhythm (SMR): a preliminary report. Biofeedback Self Regul. 1, 293–306.
Mierau, A., Hülsdünker, T., Strüder, H.K., 2015. Brain Oscillations and Athletic Performance, Sports Performance. Springer, pp. 25–36.
Mikicin, M., 2015. The autotelic involvement of attention induced by EEG neurofeedback training improves the performance of an athlete's mind. Biomed. Hum. Kinet. 7.
Moore, N.C., 2000. A review of EEG biofeedback treatment of anxiety disorders. Clin. EEG Neurosci. 31, 1–6.
Nan, W., Qu, X., Yang, L., Wan, F., Hu, Y., Mou, P., Mak, P.-I., Mak, P.U., Vai, M.I., Rosa, A., 2015. Beta/theta neurofeedback training effects in physical balance of healthy people. In: Jaffray, A.D. (Ed.), World Congress on Medical Physics and Biomedical Engineering, June 7–12, 2015. Springer International Publishing, Cham, Toronto, Canada, pp. 1213–1216.
Ninaus, M., Kober, S., Witte, M., Koschutnig, K., Neuper, C., Wood, G., 2015. Brain volumetry and self-regulation of brain activity relevant for neurofeedback. Biol. Psychol. 110, 126–133.
Park, J.L., Fairweather, M.M., Donaldson, D.I., 2015. Making the case for mobile cognition: EEG and sports performance. Neurosci. Biobehav. Rev. 52, 117–130.
Paul, M., Ganesan, S., Sandhu, J.S., 2011. Effect of sensory motor rhythm neurofeedback on psycho-physiological, electro-encephalographic measures and performance of archery players. Ibnosina J. Med. Biomed. Sci. 4, 32–39.
Pop-Jordanova, N., Demerdzieva, A., 2010. Biofeedback training for peak performance in sport case study. Macedonian J. Med. Sci. 3, 113–118.
Raymond, J., Sajid, I., Parkinson, L.A., Gruzelier, J.H., 2005. Biofeedback and dance performance: a preliminary investigation. Appl. Psychophysiol. Biofeedback 30, 65–73.
Ring, C., Cooke, A., Kavussanu, M., McIntyre, D., Masters, R., 2015. Investigating the efficacy of neurofeedback training for expediting expertise and excellence in sport. Psychol. Sport Exercise 16, 118–127.
Ros, T., Moseley, M.J., Bloom, P.A., Benjamin, L., Parkinson, L.A., Gruzelier, J.H., 2009. Optimizing microsurgical skills with EEG neurofeedback. BMC Neurosci. 10, 87.
Rostami, R., Sadeghi, H., Karami, K.A., Abadi, M.N., Salamati, P., 2012. The effects of neurofeedback on the improvement of rifle shooters' performance. J. Neurother. 16, 264–269.
Salazar, W., Landers, D.M., Petruzzello, S.J., Han, M., Crews, D.J., Kubitz, K.A., 1990. Hemispheric asymmetry, cardiac response, and performance in elite archers. Res. Q. Exerc. Sport 61, 351–359.
Sanei, S., Chambers, J.A., 2007. EEG Signal Processing. John Wiley & Sons.
Schweizer, G., Furley, P., 2016. Reproducible research in sport and exercise psychology: the role of sample sizes. Psychol. Sport Exercise 23, 114–122.
Shaw, L., Wilson, V., Nihon, S., 2012a. Getting off the bench: EEG and HRV differences between starters and nonstarters. Biofeedback 40, 34–38.
Shaw, L., Zaichkowsky, L., Wilson, V., 2012b. Setting the balance: using biofeedback and neurofeedback with gymnasts. J. Clin. Sport Psychol. 6, 47.
Sherlin, L.H., Larson, N.C., Sherlin, R.M., 2013. Developing a Performance Brain Training approach for baseball: a process analysis with descriptive data. Appl. Psychophysiol. Biofeedback 38, 29–44.
Sherlin, L.H., Ford, N.C.L., Baker, A.R., Troesch, J., 2015. Observational report of the effects of performance brain training in collegiate golfers. Biofeedback 43, 64–72.
Singer, K., 2004. The effect of neurofeedback on performance anxiety in dancers. J. Dance Med. Sci. 8, 78–81.
Strack, B., Sime, W., 2011. History of biofeedback in sport. In: Strack, B., Linden, M., Wilson, V.S. (Eds.), Biofeedback and Neurofeedback Applications in Sport Psychology. Association for Applied Psychophysiology and Biofeedback, USA, pp. 21–45.
Tan, G., Thornby, J., Hammond, D.C., Strehl, U., Canady, B., Arnemann, K., Kaiser, D.A., 2009. Meta-analysis of EEG biofeedback in treating epilepsy. Clin. EEG Neurosci. 40, 173–179.
Todd, T., 2011. Improving optimal performance-and life-for young athletes. Biofeedback 39, 109–111.
Ullsperger, M., Debener, S., 2010. Simultaneous EEG and fMRI: Recording, Analysis, and Application. Oxford University Press.
Vernon, D., Egner, T., Cooper, N., Compton, T., Neilands, C., Sheri, A., Gruzelier, J., 2003. The effect of training distinct neurofeedback protocols on aspects of cognitive performance. Int. J. Psychophysiol. 47, 75–85.
Vernon, D., Frick, A., Gruzelier, J., 2004. Neurofeedback as a treatment for ADHD: A methodological review with implications for future research. J. Neurother. 8, 53–82.
Vernon, D., Dempster, T., Bazanova, O., Rutterford, N., Pasqualini, M., Andersen, S., 2009. Alpha neurofeedback training for performance enhancement: reviewing the methodology. J. Neurother. 13, 214–227.
Vernon, D.J., 2005. Can neurofeedback training enhance performance? An evaluation of the evidence with implications for future research. Appl. Psychophysiol. Biofeedback 30, 347–364.
Walsh, V., 2014. Is sport the brain's biggest challenge? Curr. Biol. 24, R859–R860.

Wang, J.R., Hsieh, S., 2013. Neurofeedback training improves attention and working memory performance. Clin. Neurophysiol. 124, 2406–2420.
Wilson, V., Peper, E., 2011. Athletes are different: factors that differentiate biofeedback/neurofeedback for sport versus clinical practice. Biofeedback 39, 27–30.
Wilson, V.E., Peper, E., Moss, D., 2006. The mind room in Italian soccer training: the use of biofeedback and neurofeedback for optimum performance. Biofeedback 34.
Wyrwicka, W., Sterman, M.B., 1968. Instrumental conditioning of sensorimotor cortex EEG spindles in the waking cat. Physiol. Behav. 3, 703–707.
Zagha, E., McCormick, D.A., 2014. Neural control of brain state. Curr. Opin. Neurobiol. 29, 178–186.
Ziółkowski, A., Graczyk, M., Strzałkowska, A., Wilczyńska, D., Włodarczyk, P., Zarańska, B., 2012. Neuronal, cognitive and social indicators for the control of aggressive behaviors in sport. Acta Neuropsychol. 10, 537–546.
Zoefel, B., Huster, R.J., Herrmann, C.S., 2011. Neurofeedback training of the upper alpha frequency band in EEG improves cognitive performance. Neuroimage 54, 1427–1431.

Article 2

Authors: Arash Mirifar, Andreas Keil, Jürgen Beckmann, & Felix Ehrlenspiel

Title: No Effects of Neurofeedback of Beta Band Components on Reaction Time Performance

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Summary:

In a cognitively demanding task, the brain oscillatory activity in the range of Beta (13–30 Hz) has been proposed as playing a role in top-down control of attention and task execution, which could be related to increased alertness in thalamocortical systems. EEG studies, in contrast, have also shown relative increases in the power of the lower brain oscillatory activity (< 10 Hz) indicating a reduction in readiness for motor responses. In the same vein, NFT studies have shown up-regulation of brain oscillatory activity in the range of the Beta band, or reducing the ratio of the slow to fast frequencies, improves cognitive processing capabilities and leads to faster RT. This account must be approached with some caution as previous studies used different bands within the Beta frequency, which makes these results difficult to compare. For example, in one study, reinforcing the mid-beta frequency (also called Beta1, 15–18 Hz) and inhibiting the Theta frequency (4–7 Hz) led to faster RT (Egner & Gruzelier, 2004). In contrast, in another study, reinforcing a lower Beta frequency (sensory motor rhythm [SMR] 12–15 Hz) led to faster RT (Doppelmayr & Weber, 2011). These contradictory results raise questions about the neurophysiological mechanisms underpinning NFT induced-changes in behavior. Thus, this study set out to investigate the frequency specificity effects of Beta band components on different aspects of attention and RT performance, and to explore the application of the protocols on athletes. Following 2 baseline measurements, participants (N = 38, soccer players) were randomly allocated to intervention groups. Participants were trained for 10 sessions with

either TBR, or SMR, or 1 session with sham (placebo) protocols. The effect of the NFT was measured using a d2 test, and simple RT (in which participants responded to the onset of one stimulus), choice RT (in which participants responded differently to targets among non-targets stimuli), and by the power of trained frequencies in the EEG. The results of this experiment did not show a significant effect of NFT, neither in learning modifications in the trained frequency bands nor in improving attention or RT performance. The findings of this well-controlled study strongly indicate that the effects of NFT are smaller than what can be inferred from published studies. More research is needed in order to establish the effect of NFT on optimizing performance.

The manuscript was submitted on the 22nd of June 2018 and was accepted on the 3rd of September 2018; from the 18th of September 2018 this study was available online and was published in September 2019 in Journal of Cognitive Enhancement, an international peer-reviewed journal. This journal publishes studies "that contribute to deeper understanding of methods of enhancing human perception, attention, memory, cognitive control and action in healthy individuals. The range of coverage extends to meditation, video games, smart drugs, food supplements, nutrition, brain stimulation, neurofeedback, physical exercise, music, cognitive training and beyond."

Contribution:

Arash Mirifar, Jürgen Beckmann, and Felix Ehrlenspiel conceived and designed the experiments. Arash Mirifar performed the experiments. Arash Mirifar, Felix Ehrlenspiel, and Andreas Keil analyzed the data. Jürgen Beckmann and Felix Ehrlenspiel contributed reagents/materials/analysis tools. Arash Mirifar wrote the paper. All authors reviewed and edited the manuscript.

Part 1 (pilot study)

Introduction

This section is comprised of two empirical studies, the first of which is a pilot study for the second. The following section provides the theoretical definition and explains the value of a pilot study. Then, the benefits of the pilot study in the current research and its outcomes will be discussed. Finally, the main empirical study that is entitled "No Effects of Neurofeedback of Beta Band Components on Reaction Time Performance" will be presented.

A pilot study is a mini form of a full-scale experiment (also called ‘feasibility’ research) that can be run to test a particular research instrument, such as a questionnaire, or a process, such as an intervention schedule (Arain, Campbell, Cooper, & Lancaster, 2010; van Teijlingen & Hundley, 2002). Usually a pilot study is conducted once a researcher has a hypothesis about a research topic and wants to test techniques and methods, which may be applied, and determine what the research schedule may be (Hulley, Cummings, Browner, Grady, & Newman, 2013). Thus, it can be assumed such this study is a crucial element of a good study design.

A pilot study may range from a brief test of feasibility on a small number of participants to a long trial on hundreds of participants (in preparation for a major multi-year project). Baker (1994) argued that a sample of 10-20% of the sample size for the actual study is an acceptable number of participants to carry out a pilot study (Baker, 1994). Such a study should be as carefully planned as the main trial, with clear objectives and methods. Many pilot studies also focus on determining the experimental costs, such as recruiting adequate numbers of eligible participants. These kinds of studies may also be designed to demonstrate data collection instruments, data management systems, and the planned measurements are effective and efficient. A pilot study may also be used to provide estimates of parameters needed to estimate sample size. Sound estimates of the rate of the outcome or mean outcome measure in the placebo group, the effect of the intervention on the main outcome (effect size), and the statistical variability of this outcome are crucial to planning sample size. In general terms, conducting a pilot study does not guarantee success in the main study, but it does increase the likelihood of success (Arain et al., 2010; Hulley et al., 2013).

Designing and conducting a successful experiment, such as a neurofeedback intervention, requires extensive information on the type of feedback, protocol(s), and duration of the intervention; the likely effect of the intervention on the outcome; potential adverse effects of the intervention on participants; the feasibility of recruiting, randomizing, and retaining participants in the trial; and likely costs of the experiment. Often, the only way to obtain some of this information is to conduct a good pilot study. Given that, we decided to run a pilot study prior to our main study.

Method

Participants, training protocol, and study design

The design of the pilot study was pre-posttest with a control group. The NF training (NFT) included reducing the power ratio between Theta (4-7 Hz) and mid Beta (15-18 Hz) in the Theta/Beta ratio (TBR) group and enhancing power in the low Beta range (or sensory motor rhythm [SMR], 12-15 Hz) in the SMR group. Participants (N=9; with a minimum of 60 minutes activity at least 2 times per week for a minimum duration of 3 years) following the baseline measurement were equally distributed and randomly assigned to train for 4 sessions with either Theta/Beta ratio (TBR), or SMR, or 1 session with a sham protocol. Participants in the sham group were trained following the exact same protocol as the NFT groups, except that they received the feedback of registered sessions from members of the experimental groups. All participants were trained based on their brain activities at the center of the sensory-motor area, which is called Cz.

Materials and settings

Neurofeedback system settings

The NFT was carried out with a NeXus-10 MKII system and BioTrace+ software (Mind Media, B.V Netherlands). Input A (EEG channels) was set with a sampling rate of 256 Hz per second and band-pass filter setting of 1–64 Hz (IIR Butterworth Filter), and a 50-Hz notch filter was utilized. For real-time estimation of the band power, the signal was band-pass filtered (3rd order Butterworth) at the particular frequencies of interest, and the Root Mean Square (RMS) of the resulting signal (within rolling 0.125 second windows) was calculated as a metric of spectral amplitude in the frequency of interest. For each frequency band, data from electrode site Cz was recorded and the RMS amplitudes recorded from this electrode were used to generate feedback. The ranges of selected frequencies for training were: Theta (4-8 Hz), SMR (12-15 Hz), and mid-Beta (15-18 Hz). The electrode contact was monitored through the DC offset and kept below 25,000 µV RMS. In addition, the EMG artifact was monitored and kept below 5 µV. This setup was used for all groups. The reward threshold was set automatically based on the 15 sec. stats (average) and target percentages were 60% and 50% for SMR and T/B group, respectively. The required time for giving feedback and increasing scores was 500 Ms., which means that when participants in SMR or T/B groups kept their frequencies above or below the reward threshold for 500 Ms., respectively, they received feedback,.

Reaction time tasks

The effect of the training was measured by simple RT (SRT), in which participants responded to the onset of one stimulus, and by choice RT (CRT), in which participants responded differently to target and non-target stimuli. A Go/NoGo task, in which participants were asked to respond to one type of stimuli, as a target stimulus and ignore the other type, and a discriminative task, in which participants were asked to respond only to one of five stimuli as a target stimulus.

Results

The analyses of the S/CRT tests, Go/NoGo, and discriminative tasks showed that there was no significant interaction between time and group neither for the S/CRT tests nor for the Go/NoGo and discriminative tasks; SRT(median) $F(2, 9)$ =.65; p = .53 η_p^2 = .82, CRT(median) $F(2, 9)$ =.70; p = .51; η_p^2 = .09, Go/NoGo (median) $F(2, 9)$ =.02; p = .97; η_p^2 = .00,

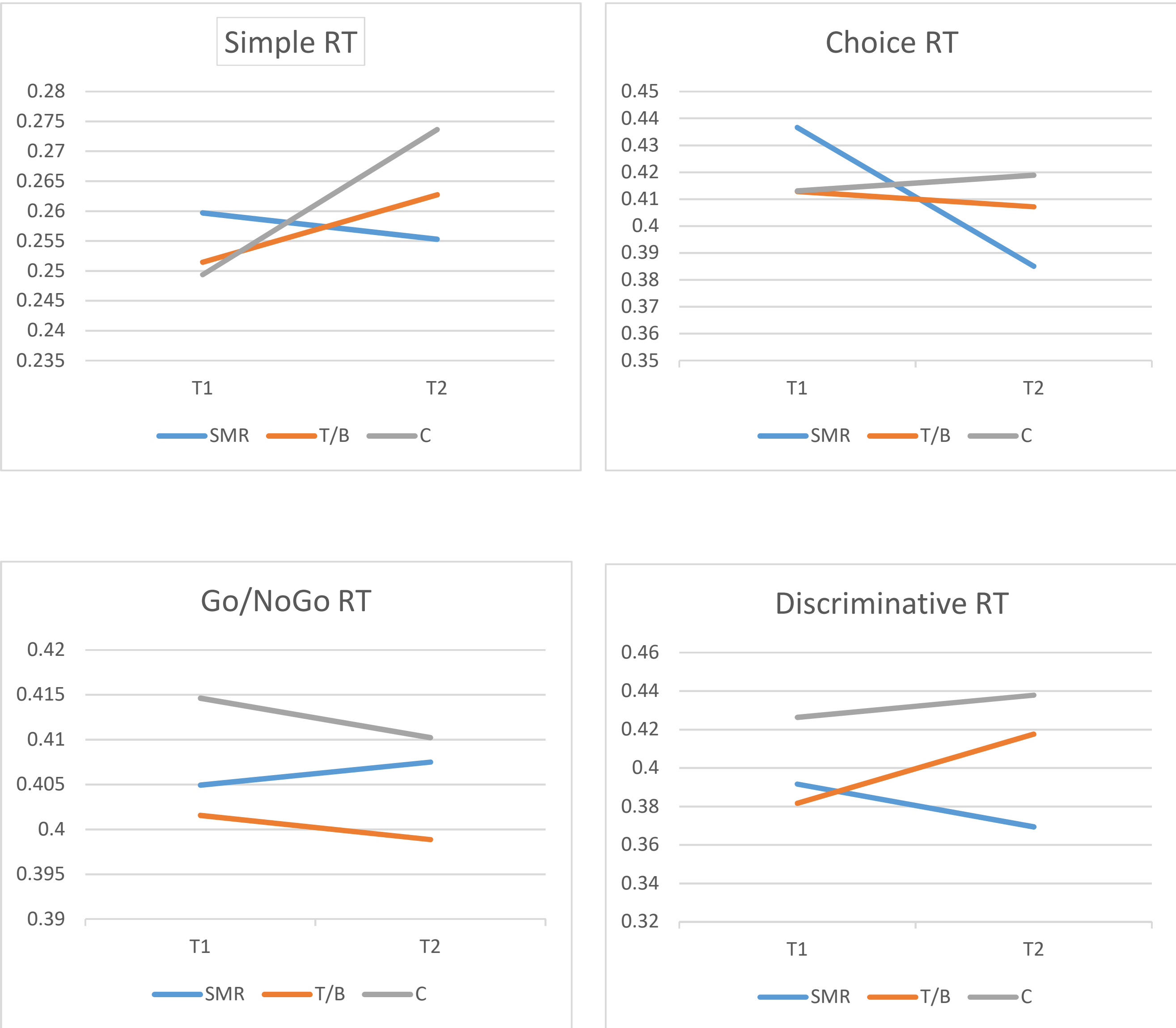

Figure 2. Descriptive results regarding performance in the simple-, choice-, Go/NoGo-, and discriminative-reaction time.

Discussion and conclusion

The present pilot study was designed to demonstrate that training protocols, design of the study and planned measurements, data collection instruments, and data management systems are feasible and efficient. Although execution of the neurofeedback training did not show a significant effect on the desired tests in this step, these results showed some improvement in S/CRT performance with different pattern between groups. These results support the feasibility and efficiency of the desired issues. In addition, by considering obtained results, we decided to focus only on two of the tests that showed more clearly the effect of the training protocols, i.e. S/CRT, and apply more training sessions to probably see significant results. Furthermore, for more precise and instructive interpretation we decided to monitor adjacent location, i.e. C3 and C4.

Part 2

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ORIGINAL ARTICLE

No Effects of Neurofeedback of Beta Band Components on Reaction Time Performance

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Abstract
Many performance situations, whether in everyday life or, e.g., in sports, require speeded responses. Reaction time (RT) in laboratory tasks—as an index of processing speed—can be improved through neurofeedback training (NFT). Learning to enhance the power of a high EEG frequency (> 10 Hz; e.g. beta band), suppressing a low frequency (< 10 Hz; e.g., theta band), or reducing the ratio between low- and high-frequency powers by means of NFT has been found to improve performance in attention and RT tasks. We aimed to test the frequency specificity of these effects on different aspects of attention and RT performance, and to explore the application of the protocols in athletes. NFT aiming to reduce the power ratio between theta (4–7 Hz) and mid-beta (15–18 Hz) ranges was compared with NFT enhancing power in the low-beta range (sensory motor rhythm [SMR] 12–15 Hz). Following two baseline measurements, participating soccer players ($N = 38$) were randomly assigned to train for 10 sessions with one of theta/beta ratio (TBR), SMR, or one session with a sham protocol. Training effects were measured by d2, simple, and choice RT tasks and by power of trained frequencies in the EEG. NFT did not lead to modifications in the trained frequency bands and was not able to improve attention or RT performance. The findings of this well-controlled study strongly indicate that the effects of NFT are smaller than what can be inferred from published studies. Clearly, more research is needed in order to establish the effect of NFT on optimizing performance.

Keywords Neurofeedback training · Attention · Reaction time · Athletes

Introduction

Many performance situations require speeded responses, including simple reactions such as braking for a child suddenly stepping onto the street and more complex reactions such as jumping by a goalkeeper for a soccer penalty kick. Therefore, reaction time (RT), an index of processing speed, has attracted attention from different disciplines including medical research, psychopharmacology, experimental psychology, and neuroscience (Nissan et al. 2013). As a standard approach, response times in suitable paradigms are used as proxies for the underlying mental processes and for the individual's ability to quickly and effectively make complex decisions and initiate actions. In sports, where speeded responses are often required, an athlete's ability to react quickly in the laboratory may therefore reflect processes underlying real-world athletic skills. Consequently, understanding whether laboratory RT can be improved by suitable training and intervention techniques is of practical importance. Neurofeedback training (NFT) has been shown to improve attention and RT in clinical and general populations, but evidence is inconclusive regarding different training protocols (Cortese et al. 2016; Mirifar et al. 2017; Xiang et al. 2018). The present study directly compares the effects of two different protocols to improve RT in the laboratory to help clarify the picture and aims to provide foundation for applications in sport by examining athletes.

NFT is a type of biofeedback training and as such an operant learning technique that promotes a user's intentional and explicit control of brain activity. As a bio-signal, typically the band power of a specific frequency range of the electroencephalogram (EEG) is assessed and fed back. To date, several studies have not only documented the effectiveness of NFT

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for different applications (e.g., see reviews Gruzelier 2014; Vernon 2005), but also evidence has accrued that changes in brain activity following NFT are accompanied by changes in gray matter volume and microstructural changes in white and gray matter (Ghaziri et al. 2013).

NFT has emerged as an alternative intervention for treating symptoms in several clinical conditions (e.g., ADHD; Lofthouse et al. 2012). NFT has also been applied in healthy persons toward increasing performance, commonly called “optimal” or “peak performance,” and the effectiveness of NFT in the domains of cognitive and music performance is well established (Egner and Gruzelier 2003). A recent systematic review for the domain of sport performance shows, however, that the application of NFT is still in its infancy and its effectiveness toward enhancing athletes’ performance is not well established (Mirifar et al. 2017); this issue was also demonstrated by a recently implemented meta-analysis in the field (Xiang et al. 2018). These reviews also point out that many of the protocols used for NFT to enhance sport performance lack evidence or a clear rationale. This study therefore aims to compare the effects of two different protocols (designated by the targeted EEG frequency band: theta/beta ratio and sensorimotor rhythm) on sustained selective attention and RT performance in athletes.

The behavioral target of NFT in sports may vary between applications in the context of RT. A speeded reaction can be simple (e.g., reacting to a starting pistol on a track and field) or complex (e.g., reacting to an opponent’s attack in Olympic fencing). A simple RT task typically creates a situation in which only one type of response is required following a given stimulus. In contrast, a choice RT task is characterized by at least two different responses mapped onto different stimuli. Each stimulus is associated with one specific response, and participants must select the correct response given the stimulus. This additional stage of processing goes beyond what is required for a simple RT task. Other parameters (e.g., motor speed, perception speed) are often seen as identical between simple RT and choice RT tasks. Thus, comparing simple RT (SRT) and choice RT (CRT) tasks enables the assessment of internal motor-cognitive processes, notably processes of attentive sensory-motor mapping and response selection (Ives 2013).

The internal motor-cognitive processes are under the effect of activation states of the cerebral cortex. Such activation could be tonic or phasic and might be relatively global or more localized. Terms that have been used to describe these states include arousal, alertness, and attention (Oken et al. 2006), and they are highlighted as multi-dimensional psychological processes, which interact directly (Coull 1998; Lindsley 1988). Regarding attention, there is no generally agreed taxonomy of attentional operations; however, there is a consensus in several issues, e.g., the view of three brain networks, which has shown to contribute to the cognitive concept of attention (Posner 2008). These networks separably implement such functions as alerting (attaining and sustaining a state of high sensitivity to incoming stimuli), orienting (excerpt data from sensory input), and executive control (engaging the mechanisms for determining and resolving conflict among perceptions, feelings, thoughts, and responses; Posner 2008; Raz and Buhle 2006). Then, it could be assumed that cognitive tasks (such as different RT tasks) with respect to their characters differently engage these networks and, as a consequence, alter the cortical and sub-cortical activity.

Regarding alertness, different frequency ranges of cortical activity have been associated with different RT tasks. The brain frequencies are mostly conventionally subdivided into five frequency bands: delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), gamma (> 30 Hz; see, e.g., Groppe et al. 2013). However, sometimes, researchers subdivide them to minor frequencies, such as delta (1–4 Hz), theta (4–7 Hz), low alpha (8–10 Hz), high alpha (10–12 Hz), low-beta (also known as SMR [12–15 Hz]), mid-beta (also known as beta1 [15–18 Hz] and beta2 [19–22 Hz]), high-beta (also known as beta3 [23–26 Hz] and beta4 [27–30 Hz]), low gamma (30–80 Hz), and high gamma (80–150 Hz; see, e.g., Abhang et al. 2016; Pimenta et al. 2018). We will use the terms SMR (12–15 Hz) and mid-beta (15–18 Hz) in this manuscript.

Brain waves in the entire beta frequency range (13–30 Hz) seem to be related to increased alertness in thalamocortical systems, for example, as measured in the cat brain (Steriade 2005). Thus, an increase in beta frequency power appears to reflect a state in which motor and or sensory cortices are activated or “primed,” thereby facilitating stimulus detection, response selection, and selective attention (Neuper and Pfurtscheller 2001). By contrast, relative increases in the power of lower-frequency activity in the human EEG (< 10 Hz) have been linked to decreased readiness for motor responses (Achim et al. 2013; Minkwitz et al. 2011). Correlational studies have shown that the power of low-frequency oscillation (2–10 Hz) is inversely related to stimulus detection. Indeed, power in this low band is reduced when observers correctly and rapidly detect simple visual stimuli, whereas power is heightened when responses are slow or erroneous (Achim et al. 2013). During best performances in an attention task, slow frequencies (e.g., low alpha 8–10 Hz) are attenuated (Oken et al. 2006). The theta/beta ratio (TBR), the ratio between power in the theta frequency (4–7 Hz) and beta frequency (13–30 Hz), is greater immediately before the onset of a missed target stimulus compared with trials with correct responses (Tsai et al. 2005). Oken et al. (2006) also pointed out that performance in a sustained attention task deteriorated when TBR increased.

NFT studies have shown that reinforcement of beta frequency oscillations improves cognitive processing capabilities and leads to faster RT (e.g., Rasey et al. 1995). However, this body of work used different bands within the beta frequency, making results difficult to compare among studies. Egner and Gruzelier (2004) showed that reinforcing the mid-beta frequency (beta1 15–18 Hz) and inhibiting the theta frequency (4–7 Hz) led to faster RT. In contrast, Doppelmayr and Weber (2011) showed that reinforcing a lower beta frequency (sensory motor rhythm [SMR] 12–15 Hz) led to faster RT. These divergent findings raise questions regarding the neurophysiological mechanisms mediating NFT-induced changes in behavior. For the mid-beta (15–18 Hz) training, it has been argued that heightened arousal mediated by increased activation in noradrenergic brain networks may in turn result in faster responses (Egner and Gruzelier 2004). Functional brain connectivity between motor areas and visual processing areas is reduced following NFT in the SMR range (12–15 Hz), indicating reduced sensorimotor interference (Doppelmayr and Weber 2011; Wang and Hsieh 2013). This finding is consistent with the observation of more accurate and faster response times following NFT compared with control conditions (Doppelmayr and Weber 2011).

In summary, the studies presented above provide evidence that NFT of higher-frequency oscillatory activity (> alpha range 8–12 Hz) leads to increased stimulus detection and faster RT compared with NFT of slow frequencies. However, the specific effects of mid-beta NFT versus SMR NFT may differ with contrasting outcome measures. There has also been little discussion on the effectiveness of the two protocols on different aspects of attention and RT performance, including in athletes. Athletes' performances and behaviors differ from those of non-athletes (Swann et al. 2015) as substantiated by neuroscientific evidence of the mechanisms underlying the plastic adaptive changes in the neuronal circuits of athletes' brains (Del Percio et al. 2007; Nakata et al. 2010). Thus, it may not be possible to generalize results obtained on non-athlete samples to athletes.

The present study therefore tests the hypothesis that NFT of mid-beta and SMR frequencies may contrastingly affect different types of responses. If increasing power in the mid-beta range and concomitantly decreasing the power in the theta range heightens cortical arousal and facilitates the reactivity of motor systems, then successful NFT of TBR oscillatory power may reduce simple RT. In contrast, if increasing power in the SMR (12–15 Hz) band reduces sensorimotor interference and thus improves response selection processes, successful NFT of SMR power is expected to primarily benefit choice behavior (i.e., reduce CRT). The study therefore aims to compare the effects of TBR and SMR frequencies on performance in different reaction and attention tasks in athletes.

We also examine the assumption that NFT alters brain oscillations by selectively affecting the targeted frequencies. Most studies in the field of peak performance have not reported the extent to which any behavioral changes are related to changes in brain patterns as a consequence of NFT (Mirifar et al. 2017). To address this, we investigate the effects of NFT on the spectrum of ongoing EEG recordings. We track brain activity changes within and between sessions as well as during test performance. The hypothesis that NFT selectively affects targeted frequency bands would be supported if spectral power in targeted bands varies as a function of the condition (NFT of TBR vs. SMR) and time point (second pretest vs. post-test). Finally, we quantify measurement reliability for dependent variables in repeated sessions by introducing two baseline measurement times. This approach allows us to quantify noise levels in behavioral and EEG measurements, as well as training, habituation, and temporal effects.

Materials and Methods

Participants

Team-sport athletes with similar training backgrounds were recruited to ensure homogeneity of the sample. Inclusion criteria required that participants' age ranged between 14 and 24 years, to match the age in the studies by Egner and Gruzelier (2004) and Doppelmayr and Weber (2011). The participants had a record of regular exercise, with a minimum of 90-min activity at least four times per week for a minimum of 4 years. We followed the criteria laid out in the recent review by Swann et al. (2015) to evaluate the quality of athletes as participants. Individuals were excluded if they had any background in NFT or reported any history of neurologic (e.g., brain injury), medical (e.g., diabetes), or psychiatric conditions (e.g., attention-deficit hyperactivity disorder) known to affect cognition. Individuals taking prescription drugs or participating in other cognitive training activities were also excluded. Sample size was calculated a priori using G*Power (Faul et al. 2007) with the following settings: F test, repeated measures, within-between interaction, power $1-\beta=0.95$, $\alpha=05$, set for three groups and two times measurement. Correlation among repeated measurements was set to 0.8 because a pilot study had shown high correlations between measurements of RT. The two of relevant studies that form the basis for this study did not report effect size nor standard deviation (Doppelmayr and Weber 2011 [$n=14$/group]; Egner and Gruzelier 2004 [$n=8$/group]). So, the standard small to medium effect size of $f=.20$ was used for calculations. This resulted in a required sample size of 45 (15 participants per group). Thus, we recruited 45 male soccer players as participants, and from this group, 38 participants (age range 14–23 years; M = 16.76, SD = 2.47) completed the experiment. Participants were randomly assigned to one of the three groups that received different NFT protocols (Table 1). Two left-handed participants were randomly assigned to one of the experimental groups. Participants provided informed consent before taking part, and the study was approved by the ethics committee of Technical University of Munich.

Table 1 Characteristics of the participants

Group			
Characteristics	SMR	Theta/beta	Control
N	13	13	12
Age (M ± SD)	16.46 ± 2.29	17.38 ± 2.29	16.41 ± 2.29

Study Design

The study adopted a mixed-multifactorial design. Participants attended an initial pretest, a second pretest, and a post-test. The initial pretest and post-test were set 24 days apart. The gap between the initial pretest and the second pretest and between the last intervention session and the post-test was 48 h (M = 49.05, SD = 8.33 and M = 48.06, SD = 3.15, respectively). Participants in the two intervention groups completed 10 training sessions that took place every other day over a period of 20 days. Any missed training sessions were made up by participants during the same time period. The number of intervention sessions in this experiment was developed based on studies that applied one of the desired protocols on healthy participants and showed significant effects (e.g., Egner and Gruzelier 2004; Kober et al. 2015; Vernon et al. 2003). Participants in the control group received one sham intervention session that was occurred 48 h before the post-test (M = 48.20, SD = 3.41) (Fig. 1).

Training Protocols

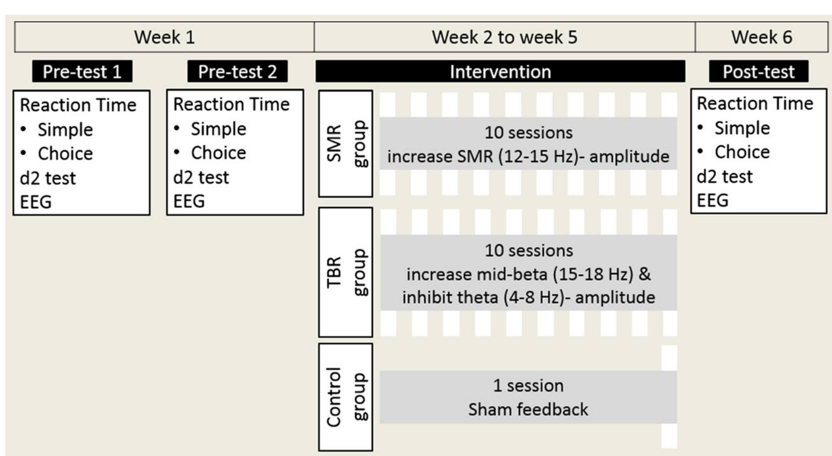
The TBR and SMR protocols were applied based on descriptions by Egner and Gruzelier (2004) and Doppelmayr and Weber (2011). In the TBR group, participants were trained to decrease TBR (i.e., decrease theta and simultaneously increase mid-beta amplitude). In the SMR group, participants were trained to increase the amplitude of SMR. The studies mentioned chose electrodes near sensory and motor cortical areas for their interventions: Participants were trained at Cz in the study by Egner and Gruzelier (2004), and at C3 and C4 in the study by Doppelmayr and Weber (2011). There are, also, studies that provided feedback based on brain oscillatory activity in the range of SMR frequency (12–15 Hz) from Cz showed improvements in attention performance and response time (e.g., Kober et al. 2015; Vernon et al. 2003). Cz was therefore chosen as the center of the sensory-motor area in this study. Feedback was given based on brain activity at Cz (according to the 10–20 system) in the form of a depiction of a light bulb on a computer screen along with a reward ("score" and auditory "beeps"). The intervention for the participants in the control group was a single sham feedback session. The sham feedback was used from the first registered session and obtained from a randomly paired member of the intervention groups.

NF System and Settings

NFT was carried out with the NeXus-10 MKII system and BioTrace+ software (Mind Media, B.V., the Netherlands). Inputs A and B (EEG channels) were set with a sampling rate of 256 Hz and a band-pass filter setting of 1–64 Hz (IIR Butterworth Filter). A 50-Hz notch filter was used. For real-time estimation of band power, the signal was band-pass filtered (third-order Butterworth) at the particular frequencies of interest. The root mean square (RMS) of the resulting signal within rolling 0.125-s windows was calculated as a measure of spectral amplitude in the frequency of interest. For the respective frequency bands, data from electrode sites C3, Cz, and C4 were recorded, but only the RMS amplitude recorded from the electrode at Cz was used to generate feedback. The ranges of selected frequencies for training were as follows: theta (4–8 Hz), SMR (12–15 Hz), and mid-beta (15–18 Hz). Electrode contact was monitored through the DC offset and kept below 25,000 μV RMS. The EMG artifact was monitored and kept below 5 μV. This setup was used for all groups.

Regarding threshold settings, we followed the general guidelines for threshold settings by Demos (2005, pp. 75–80) because specifications in the original studies (Doppelmayr and Weber 2011; Egner and Gruzelier 2004)

Fig. 1 Study design



either differed or were not available. The reward threshold was set automatically based on the 15-s stats (average). Target percentages were 60 and 50% for SMR and T/B group, respectively. The required time for providing feedback and increasing scores was 500 ms. When participants kept their frequencies above (SMR group) or below (T/B group) the reward threshold for 500 ms, they received feedback. The purpose was to train participants to sustain changes in the desired direction (Congedo et al. 2004; Fuchs et al. 2003; Yang et al. 2018).

d2-Concentration Test

The d2 test is a timed paper-pencil test that assesses selective attention (Brickenkamp et al. 2010). The test consists of 14 rows of 47 items ($N = 658$). The task consists in discriminating and canceling targets from visually similar nontargets. There are 16 different types of characters, each consisting of the letters "d" or "p" with one, two, three, or four small quotation marks. The participants are required to scan the characters and mark all d characters with two quotation marks that can appear either above, below, or separated, with one mark appearing above and the other mark below. The letter d accompanied by one, three, or four quotation marks and the letter p regardless of the number of quotation marks are distractors. The participants are given 20 s per line (a total of 4 min 40 s) to complete the test.

Multiple performance scores are derived from the d2 test. The raw score E is the sum of all mistakes: errors of omission (E1) and errors of commission (E2). Errors of omission occur when target items are missed. E1 is a common mistake and is sensitive to attentional control, rule compliance, accuracy of visual scanning, and quality of performance. Errors of commission occur when nontarget items are marked. E2 is a less common error and is associated with inhibitory control, rule compliance, accuracy of visual scanning, carefulness, and cognitive flexibility. TN is the number of both relevant and irrelevant items that are processed. TN-E is the total number of items scanned minus the raw score (E). Finally, concentration performance (CP) is derived from the numbers of correctly crossed out items (d2) minus the errors of commission (E2). CP provides an index of coordination of speed and accuracy of performance (Moore and Malinowski 2009).

RT Tasks

RT tasks were programmed and implemented in MATLAB (the MathWorks Inc., Natick, MA; USA) and the Psychtoolbox extensions (http://psychtoolbox.org/). Both tasks consisted of two phases: warm-up and main test. In the simple RT task, a total of 40 stimuli were presented, and the mean interstimulus interval (ISI) was 2.5 s (drawn from a rectangular distribution with a minimum of 1 s and maximum of 4 s). The stimulus in the simple RT task was a red circle (2° of visual angle) shown on a gray background. Participants responded to the stimulus by pressing the "Enter" key with the right index finger at the right corner of the keyboard. Stimulus durations were fixed at 100 ms. The simple RT task session required ~ 2.5 min.

The choice RT task was adapted from a previous (see Woods et al. 2015) study and consisted of two types of stimuli: target "blue P" and nontarget "orange P," "blue F," or "orange F." A total of 140 stimuli were presented and 56 of them (40%) were target stimuli. Stimuli were presented on the same gray background as for the simple RT task. The target stimulus was responded to with the "D" key, and nontarget stimuli were responded to with the "K" key, with the right or left index fingers, respectively. Stimulus durations were fixed at 200 ms. In an attempt to make the CRT task challenging, ISI began at 2.5 s (compared to 3.0 s in Woods et al. 2015) and was adapted as a function of accuracy, with two subsequent correct responses (hits) leading to a 3% ISI decrease, and each error or miss leading to a 3% ISI increase. The choice RT session required ~ 6 min.

Performance in the simple RT task was indexed by the median of the 40 response times (simple reaction time [SRT]). Performance in the choice RT task was indexed by the median of the 56 target response times (CRT), central processing time (CPT), and continued feature processing time (CFPT). The CPT was derived from subtracting median CRT from median SRT, and the CFPT was derived as the difference between median response times to distractors with target color or shape and median response times to distractors with no target features.

Procedure

Test Sessions

Basic information about procedures was given to participants before performing the initial pretest. All participants completed the tests in the same order: d2 test, simple RT, and then choice RT task at three assessment times (initial pretest, second pretest, and post-test). Following the d2 test, participants' scalps were prepared with Nuprep, and electrodes were attached with Ten20 conductive paste. Electrodes were placed at C3, Cz, and C4 with a reference on the left earlobe and a ground electrode on the right earlobe. C3 and C4 were monitored to control for possible changes in adjacent locations. All participants were instructed to respond as fast and as accurately as possible to the stimuli that were presented on the screen (15.6″). During the tests, participants sat comfortably on a padded chair in a silent room with the researcher. Each assessment lasted ~ 25 min including preparation time.

Intervention (Training) Sessions

Basic information on NFT and the intervention procedure was provided to participants before performing the first intervention session. The same preparation as applied to the test sessions was applied to the intervention sessions. All participants in the intervention sessions were asked to focus their attention on a light bulb on a computer screen (15.4″) that was 1 m in front of them and to heighten its luminance for as long as possible. Each training session began with a 2-min resting condition with open eyes. Each intervention session was composed of four 5-min blocks of NFT interrupted by short breaks.

Data Reduction

EEG data reduction was automatically conducted offline using the BioTrace+ software. Artifact rejection was applied using visual inspection. A fast Fourier transformation on adjacent 2-s segments was conducted on the selected segments, resulting in a frequency resolution of 0.5 Hz. Each segment was tapered with a standard hamming window.

Statistical Analyses

Validation Analyses and Methodological Checks

Learning effects due to test repetition were assessed by subjecting the median of S/CRT and mean of the d2 test items to a 3 × 2 ANOVA (group, time [initial pretest and second pretest]) with repeated measures on the latter. Correlation analysis was used to identify the reliability of the dependent variables and potential training effects among sessions.

Behavioral Data

Effects of NFT group on S/CRT and the mean of the d2 test items were evaluated using a 3 (groups) × 2 (time) ANOVA with a repeated factor of time (second pretest and post-test).

Spectral Power Within and Between Sessions

To characterize the learning to modify spectral power between and within sessions, the mean of the amplitude of the trained frequencies between the experimental groups was analyzed with a 2 × 2 × 2 ANOVA (group, sessions [session 1 and session 10], and blocks [baseline before session and last block of session]) with repeated measures.

Spectral Power During Test Performance (RT Task)

To evaluate the effectiveness of NFT and control training to modify spectral power during performance (simple/choice RT tasks), the mean of amplitude of the trained frequencies between the groups was analyzed with a 3 × 2 ANOVA (group, time [second pretest and post-test]) with repeated measures. When appropriate, degrees of freedom were corrected using the Greenhouse–Geisser procedure. The least significant difference method was used for post hoc comparisons ($p < 0.05$; Cohen 1992).

Results

Validation Analyses and Method Checks

Analyses of the S/CRT from initial pretest to second pretest revealed that there were no significant interactions between time and group in SRT or CRT: SRT (median), $F(2, 35) = 3.13$, $p = 0.056$, $\eta_p^2 = 0.15$; SRT (error) $F(2, 35) = 1.04$, $p = 0.36$, $\eta_p^2 = 0.05$; RT of target stimuli $F(2, 35) = 0.51$, $p = 0.60$, $\eta_p^2 = 0.02$; CPT for target stimuli $F(2, 35) = 0.06$, $p = 0.93$, $\eta_p^2 = 0.00$; mean of CPT $F(2, 35) = 0.00$, $p = 0.99$, $\eta_p^2 = 0.00$; and CFPT $F(2, 35) = 0.09$, $p = 0.91$, $\eta_p^2 = 0.00$. Analyses of the d2 test from initial pretest to second pretest also revealed that there were no significant interactions between time and group in any of the items: E $F(2,35) = 0.28$, $p = 0.75$, $\eta_p^2 = 0.01$; E1 $F(2,35) = 0.07$, $p = 0.93$, $\eta_p^2 = 0.00$; E2 $F(2,35) = 0.66$, $p = 0.52$, $\eta_p^2 = 0.03$; TN $F(2,35) = 1.36$, $p = 0.26$, $\eta_p^2 = 0.07$; TN-E $F(2,35) = 1.75$, $p = 0.18$, $\eta_p^2 = 0.09$; and CP $F(2,35) = 1.71$, $p = 0.19$, $\eta_p^2 = 0.08$.

Results of the correlational analysis for S/CRT from initial pretest to second pretest were as follows: SRT $r(36) = 0.73$, $p = 0.00$; SRT (error) $r(36) = 0.17$, $p = 0.28$; RT of target stimuli $r(36) = 0.51$, $p = 0.00$; CPT $r(36) = 0.39$, $p = 0.01$; and CFPT $r(36) = 0.26$, $p = 0.11$. There was also a significant positive correlation between d2 test items from initial pretest to second pretest: E $r(36) = 0.90$, $p = 0.00$; E1 $r(36) = 0.89$, $p = 0.00$; E2 $r(36) = 0.55$, $p = 0.00$, TN $r(36) = 0.91$, $p = 0.00$; TN-E $r(36) = 0.87$, $p = 0.00$; and CP $r(36) = 0.73$, $p = 0.00$.

Behavioral Data

The first question addressed the effects of real versus control NFT on S/CRT and attention performance. Analyses of the RT test revealed no significant interactions between time and group in the SRT or the CRT: SRT (median) $F(2, 35) = 0.30$, $p = 0.74$, $\eta_p^2 = 0.01$; SRT (error) $F(2, 35) = 0.62$, $p = 0.54$, $\eta_p^2 = 0.03$; RT of target stimuli $F(2, 35) = 1.58$, $p = 0.22$, $\eta_p^2 = 0.08$; CPT for target stimuli $F(2, 35) = 1.84$, $p = 0.17$, $\eta_p^2 = 0.09$; mean of CPT $F(2, 35) = 0.59$, $p = 0.55$, $\eta_p^2 = 0.03$; and CFPT $F(2, 35) = 0.95$, $p = 0.39$, $\eta_p^2 = 0.05$. No significant interactions between time and group for any of the dependent variables were found in the d2 tests: E $F(2, 35) = 1.09$, $p =$

0.34, η_p^2 = 0.05; E1 $F(2,35) = 1.39$, $p = 0.26$, η_p^2 = 0.07; E2 $F(2,35) = 1.02$, $p = 0.36$, η_p^2 = 0.05; TN $F(2, 35) = 0.18$, p = 0.83, η_p^2 = 0.01; TN-E $F(2, 35) = 0.28$, $p = 0.75$, η_p^2 = 0.01; and CP $F(2, 35) = 0.11$, $p = 0.89$, η_p^2 = 0.00 (Fig. 2).

Effects of NFT on Spectral Power Within and Between Sessions

We assessed changes in spectral power between and within sessions as a function of NFT. Analyses showed no significant interactions between session, block, and group for TBR at Cz, $F(1, 24) = 0.012$, $p = 0.91$, η_p^2 = 0.00. None of the other effects were significant (all $p > .10$), except for a significant interaction between block and group, $F(1, 24) = 6.34$, $p = 0.01$, η_p^2 = 0.20. The ratio of theta to mid-beta was increased in the SMR group within sessions. Analyses of SMR at Cz showed no interaction between session, block, and group, $F(1, 24)$ = 1.96, $p = 0.17$, η_p^2 = 0.07, nor for any of the other effects (all $p > .10$).

Effects of NFT on Spectral Power During Test Performance (RT Task)

Analyses of spectral power at the trained frequencies revealed no significant interactions between time and group during the simple RT task, $F(2, 34) = 0.23$, $p = 0.79$, η_p^2 = 0.01; and $F(2, 34) = 1.09$, $p = 0.34$, η_p^2 = 0.06, for TBR and SMR, respectively. There were also no significant interactions during the choice RT task, $F(2, 35) = 0.46$, $p = 0.63$, η_p^2 = 0.02; and $F(2, 35) = 1.28$, $p = 0.28$, η_p^2 = 0.06, for TBR and SMR, respectively. Comparable effects were seen at channels C3 and C4.

Discussion

Recent reviews emphasize the effectiveness of NFT in optimizing performance (Gruzelier 2014). However, Mirifar et al. (2017) highlight the weakness of evidence on sport performance enhancement with NFT. This may reflect the lack of a principled approach for selecting a specific NFT protocol or the lack of neurophysiological evidence for specific mechanisms mediating behavioral outcomes. This conclusion was also confirmed by the current meta-analytic review that showed that the effectiveness of NFT on sport performance was moderated by control group design (Xiang et al. 2018). Regarding improving speeded responses through NFT, two different protocols have been discussed in the past. The main aim of the study was thus to compare the effects of TBR and SMR protocols on attention and RT performance of athletes. Attention was evaluated using the d2 test and the numbers of omission and commission errors in the choice RT task. RT performance was evaluated in a simple (SRT) and a choice reaction time task (CRT). Addressing concerns relating to the methodological quality of studies on NFT in sport (Mirifar et al. 2017), the present study also included a larger sample to increase power, a control group, and multiple training sessions to examine the specificity and stability of NFT-related effects. Most importantly, not only behavioral outcomes but also neurophysiological changes were examined as a result of NFT.

Regarding these neurophysiological changes, we found no modification of brain activity between baseline rest conditions through intervention. This part of the finding was expected as, in general, the aim of NFT when employed to optimize performance is to change brain activity only within sessions and during execution of a specific task, but not outside of these conditions. We also did not find any evidence for modifications in brain oscillations during NFT and during test performance; thus, our hypothesis that NFT would lead

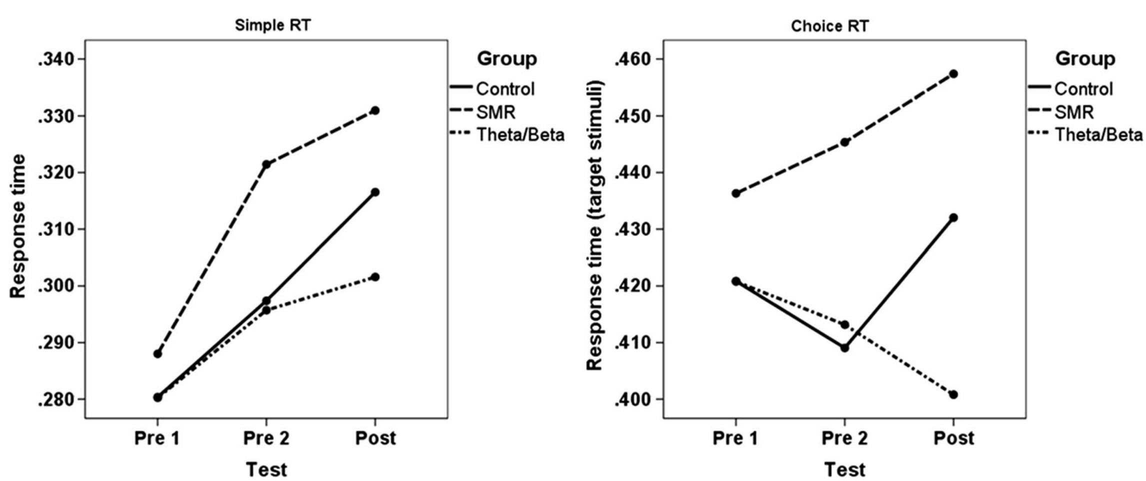


Fig. 2 Descriptive results regarding performance in the simple reaction time task (left) and the choice reaction time task (right)

to protocol specific modifications in the trained frequencies was not supported.

Furthermore, our hypotheses regarding the behavioral outcomes were not supported. Neither of the groups showed improvement in attention performance. Our hypothesis that TBR training would selectively improve SRT performance and that SMR training would selectively improve CRT performance was also not supported.

Thus, we were not able to replicate findings by Egner and Gruzelier (2004) who evaluated the effectiveness of NFT on RT performance. They found faster RT and increased target P300 amplitudes after TBR training but not SMR training. But, their study did not provide evidence for underlying neurophysiological changes, neither within and between sessions nor during task performance. In a follow-up study (Pimenta et al. 2018) applying the protocol, no frequency-specific effects could be found with respect to between session modifications of the trained frequencies. Thus, it is difficult to attribute the protocol specific behavioral effects to underlying neurophysiological modifications. Our results are partially in line with those of Doppelmayr and Weber (2011), who also compared the effectiveness of SMR and TBR training on attention and RT performance. Whereas they similarly found no effects of NFT on d2 attention performance, they found faster SRT and CRT performance only after SMR training. In this case, this improvement in RT performance was linked to modulations of SMR activity during training.

Still, it is difficult to understand the protocol specific behavioral effects for at least two reasons. Firstly, Doppelmayr and Weber (2011) failed to address the contribution of the adjacent mid-beta (15–18 Hz) on the results attributed to the SMR protocol because they reported only changes of SMR activity but did not report results regarding mid-beta (15–18 Hz) band. To show, these specific changes would be important because Pimenta et al. (2018) showed that SMR and TBR training led to similar enhancements in amplitude in the SMR and mid-beta band. Secondly, it still needs to be shown that changes in SMR activity transfer from training sessions to test performance. In comparison to the study by Doppelmayr and Weber (2011), it is a strength of our study that we compared neurophysiological activity not only within and between training sessions but also between test sessions.

There are some more differences in our study compared to the previous studies that could explain differences in results. By following general guidelines for NFT (Demos 2005) we used different threshold settings compared to the settings reported by Doppelmayr and Weber (2011). It could be that setting thresholds automatically (instead of manually) and the time required above threshold at 500 ms (compared to 250 ms) leads to poorer neurofeedback learning because of less immediate experience of success. Although commenting on required time for giving a reward, e.g., Congedo et al. (2004, p. 391) argue that maintaining a desirable change for at least 500 ms leads to sustain changes in the desired direction. A further reason for failing to replicate could be that we assessed a sample of athletes. On the neurophysiological level, athletes show different functional and structural plasticity compared to non-athletes (Del Percio et al. 2008; Nakata et al. 2010). Athletes' brains have adapted to the demands on speeded responses of their sports, and thus, there may be less potential for neurophysiological adaptations through NFT. On the behavioral level, tests used may have not been specific enough to detect subtle changes. Attention tests such as d2 are designed to assess executive functions in patients and ordinary persons, not athletes. A meta-analytic review (Voss et al. 2010) concluded that higher-level cognitive tasks should be applied to athletes because athletes perform better on measures of processing speed and some attentional paradigms in laboratory-based tasks. This highlights that conclusions drawn from the general population may not easily be transferred to a more specific population like athletes. Adding a control group of non-athletes to verify the occurrence of such floor effects could yield insights in the future. The results also point to the effects of NFT being probably smaller than previously reported, at least in athletes. The study therefore may have been underpowered although sample size was a priori determined to detect small effect sizes. It was also comparable with or larger than previous studies, and a mixed design with repeated measurements and a control group was leveraged. If the effect of NFT on neurophysiological modifications, attention, and RT performance is indeed smaller than assumed, this also necessitates more intensive and/or extensive interventions. Guidelines previously suggested that NFT should comprise at least four sessions (Konareva 2005) or up to 10 sessions (Gruzelier et al. 2006). Our results suggest that even 10 training sessions may have been insufficient to elicit changes. In fact, Doppelmayr and Weber (2011) found changes in spectral power in SMR and related improvements in RT performance after 30 sessions.

Viewed from a more general perspective, our results could also fuel the continuing debate about the effectiveness of NFT for optimizing performance, and additionally, the effectiveness of NFT in general. In an early review on performance enhancement, Vernon (2005) raised concerns that conclusive evidence on the effectiveness of NFT to enhance performance was missing. In contrast, Gruzelier (2014) in a later systematic review summed up his findings to show that NFT in the general populations is effective to enhance various performance measures. Current systematic and meta-analytic reviews (Mirifar et al. 2017; Xiang et al. 2018) in the sport domain again have raised doubts and argued that studies show only a weak link between NFT and (sport) performance enhancement. Importantly, these reviews showed that effects of NFT on performance in the sport domain were moderated by control group design. That means, when analyses were limited to studies that employed active/placebo controls, there was no clear evidence for the effectiveness of NFT. Thus, the efficacy of NFT applied in sport performance might be fairly weak. This challenge is not limited to non-clinical applications of optimizing performance. For clinical applications, even in the case of ADHD—which has been considered a hallmark of NFT since the seminal studies by Lubar and Shouse (1976)—the evidence for indications and specific protocols appears to be weak, raising concerns about the use of NFT in clinical practice (see, e.g., Arns et al. 2017). Further highlighting the importance of controlling for placebo effects in NFT and raising more general concerns, Thibault and Raz (2017) argued that "the comparable benefits of veritable-versus-sham feedback, conflicts of interest, and a weak theoretical underpinning, advocating for EEG-NF poses a conundrum". The results of our controlled study do not add to solve the conundrum and suggest that evidence for advocating for frequency-specific NFT to improve attention and RT in athletes is weak.

Author Contributions AM, FE, and JB: conceived and designed the experiments. AM: performed the experiments. AM, FE, and AK: analyzed the data. Contributed reagents/materials/analysis tools: FE and JB. AM: Wrote the paper.

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Compliance with Ethical Standards

Participants provided informed consent before taking part, and the study was approved by the ethics committee of Technical University of Munich.

Conflict of Interest The authors declare that they have no competing interests.

References

Abhang, P. A., Gawali, B. W., & Mehrotra, S. C. (2016). Chapter 3—technical aspects of brain rhythms and speech parameters. In P. A. Abhang, B. W. Gawali & S. C. Mehrotra (Eds.), Introduction to EEG- and Speech-Based Emotion Recognition (pp. 51-79): Academic press.

Achim, A., Bouchard, J., & Braun, C. M. (2013). EEG amplitude spectra before near threshold visual presentations differentially predict detection/omission and short-long reaction time outcomes. *International Journal of Psychophysiology, 89*(1), 88–98. https://doi.org/10.1016/j.ijpsycho.2013.05.016.

Arns, M., Batail, J.-M., Bioulac, S., Congedo, M., Daudet, C., Drapier, D., . . . Lotte, F. (2017). Neurofeedback: one of today's techniques in psychiatry? L'Encéphale, 43(2), 135–145.

Brickenkamp, R., Schmidt-Atzert, L., & Liepmann, D. (2010). *Test d2 - Revision. Aufmerksamkeits- und Konzentrationstest*. Göttingen: Verlag für Psychologie Hogrefe.

Cohen, J. (1992). A power primer. *Psychological Bulletin, 112*(1), 155.

Congedo, M., Lubar, J. F., & Joffe, D. (2004). Low-resolution electromagnetic tomography neurofeedback. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 12*(4), 387–397. https://doi.org/10.1109/TNSRE.2004.840492.

Cortese, S., Ferrin, M., Brandeis, D., Holtmann, M., Aggensteiner, P., Daley, D., . . . European, A. G. G. (2016). Neurofeedback for attention-deficit/hyperactivity disorder: meta-analysis of clinical and neuropsychological outcomes from randomized controlled trials. Journal of the American Academy of Child and Adolescent Psychiatry, 55(6), 444–455. https://doi.org/10.1016/j.jaac.2016.03.007.

Coull, J. T. (1998). Neural correlates of attention and arousal: insights from electrophysiology, functional neuroimaging and psychopharmacology. *Progress in Neurobiology, 55*(4), 343–361. https://doi.org/10.1016/S0301-0082(98)00011-2.

Del Percio, C., Brancucci, A., Vecchio, F., Marzano, N., Pirritano, M., Meccariello, E., . . . Eusebi, F. (2007). Visual event-related potentials in elite and amateur athletes. Brain Research Bulletin, 74(1), 104–112. https://doi.org/10.1016/j.brainresbull.2007.05.011.

Del Percio C., Rossini, P. M., Marzano, N., Iacoboni, M., Infarinato, F., Aschieri, P., . . . Eusebi, F. (2008). Is there a "neural efficiency" in athletes? A high-resolution EEG study. Neuroimage, 42(4), 1544–1553. https://doi.org/10.1016/j.neuroimage.2008.05.061.

Demos, J. N. (2005). Getting Started with Neurofeedback: W. W. Norton.

Doppelmayr, M., & Weber, E. (2011). Effects of SMR and theta/beta neurofeedback on reaction times, spatial abilities, and creativity. *Journal of Neurotherapy, 15*(2), 115–129. https://doi.org/10.1080/10874208.2011.570689.

Egner, T., & Gruzelier, J. H. (2003). Ecological validity of neurofeedback: modulation of slow wave EEG enhances musical performance. *Neuroreport, 14*(9), 1221–1224. https://doi.org/10.1097/01.wnr.0000081875.45938.d1.

Egner, T., & Gruzelier, J. H. (2004). EEG biofeedback of low beta band components: frequency-specific effects on variables of attention and event-related brain potentials. *Clinical Neurophysiology, 115*(1), 131–139.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191.

Fuchs, T., Birbaumer, N., Lutzenberger, W., Gruzelier, J. H., & Kaiser, J. (2003). Neurofeedback treatment for attention-deficit/hyperactivity disorder in children: a comparison with methylphenidate. *Applied Psychophysiology and Biofeedback, 28*(1), 1–12.

Ghaziri, J., Tucholka, A., Larue, V., Blanchette-Sylvestre, M., Reyburn, G., Gilbert, G., . . . Beauregard, M. (2013). Neurofeedback training induces changes in white and gray matter. Clinical EEG and Neuroscience, 44(4), 265–272. https://doi.org/10.1177/1550059413476031.

Groppe, D. M., Bickel, S., Keller, C. J., Jain, S. K., Hwang, S. T., Harden, C., & Mehta, A. D. (2013). Dominant frequencies of resting human brain activity as measured by the electrocorticogram. *Neuroimage, 79*, 223–233.

Gruzelier, J. H. (2014). EEG-neurofeedback for optimising performance. I: a review of cognitive and affective outcome in healthy participants. *Neuroscience & Biobehavioral Reviews, 44*, 124–141.

Gruzelier, J. H., Egner, T., & Vernon, D. (2006). Validating the efficacy of neurofeedback for optimising performance. *Progress in Brain Research, 159*, 421–431. https://doi.org/10.1016/S0079-6123(06)59027-2.

Ives, J. C. (2013). Motor Behavior: Connecting Mind and Body for Optimal Performance: Wolters Kluwer/Lippincott Williams & Wilkins.

Kober, S. E., Witte, M., Stangl, M., Väljamäe, A., Neuper, C., & Wood, G. (2015). Shutting down sensorimotor interference unblocks the networks for stimulus processing: an SMR neurofeedback training study. *Clinical Neurophysiology, 126*(1), 82–95. https://doi.org/10.1016/j.clinph.2014.03.031.

Konareva, I. (2005). Modifications of the EEG frequency pattern in humans related to a single neurofeedback session. *Neurophysiology, 37*(5–6), 388–395.

Lindsley, D. B. (1988). *Activation, arousal, alertness, and attention States of Brain and Mind* (pp. 1–3). Boston: Birkhäuser Boston.

Lofthouse, N., Arnold, L. E., Hersch, S., Hurt, E., & DeBeus, R. (2012). A review of neurofeedback treatment for pediatric ADHD. *Journal of Attention Disorders, 16*(5), 351–372.

Lubar, J. F., & Shouse, M. N. (1976). EEG and behavioral changes in a hyperkinetic child concurrent with training of the sensorimotor rhythm (SMR): a preliminary report. *Biofeedback and Self-Regulation, 1*(3), 293–306.

Minkwitz, J., Trenner, M. U., Sander, C., Olbrich, S., Sheldrick, A. J., Schönknecht, P., . . . Himmerich, H. (2011). Prestimulus vigilance predicts response speed in an easy visual discrimination task. Behavioral and Brain Functions*,* 7(1), 31.

Mirifar, A., Beckmann, J., & Ehrlenspiel, F. (2017). Neurofeedback as supplementary training for optimizing athletes' performance: a systematic review with implications for future research. *Neuroscience and Biobehavioral Reviews, 75*, 419–432. https://doi.org/10.1016/j.neubiorev.2017.02.005.

Moore, A., & Malinowski, P. (2009). Meditation, mindfulness and cognitive flexibility. *Consciousness and Cognition, 18*(1), 176–186. https://doi.org/10.1016/j.concog.2008.12.008.

Nakata, H., Yoshie, M., Miura, A., & Kudo, K. (2010). Characteristics of the athletes' brain: evidence from neurophysiology and neuroimaging. *Brain Research Reviews, 62*(2), 197–211.

Neuper, C., & Pfurtscheller, G. (2001). Event-related dynamics of cortical rhythms: frequency-specific features and functional correlates. *International Journal of Psychophysiology, 43*(1), 41–58. https://doi.org/10.1016/S0167-8760(01)00178-7.

Nissan, J., Liewald, D., & Deary, I. J. (2013). Reaction time and intelligence: comparing associations based on two response modes. *Intelligence, 41*(5), 622–630. https://doi.org/10.1016/j.intell.2013.08.002.

Oken, B., Salinsky, M., & Elsas, S. (2006). Vigilance, alertness, or sustained attention: physiological basis and measurement. *Clinical Neurophysiology, 117*(9), 1885–1901. https://doi.org/10.1016/j.clinph.2006.01.017.

Pimenta, M. G., van Run, C., de Fockert, J. W., & Gruzelier, J. H. (2018). Neurofeedback of SMR and beta1 frequencies: an investigation of learning indices and frequency-specific effects. *Neuroscience, 378*, 211–224. https://doi.org/10.1016/j.neuroscience.2017.07.056.

Posner, M. I. (2008). Measuring alertness. *Annals of the New York Academy of Sciences, 1129*(1), 193–199. https://doi.org/10.1196/annals.1417.011.

Rasey, H., Lubar, J. F., McIntyre, A., Zoffuto, A., & Abbott, P. L. (1995). EEG biofeedback for the enhancement of attentional processing in normal college students. *Journal of Neurotherapy, 1*(3), 15–21. https://doi.org/10.1300/J184v01n03_03.

Raz, A., & Buhle, J. (2006). Typologies of attentional networks. *Nature Reviews. Neuroscience, 7*(5), 367–379. https://doi.org/10.1038/nrn1903.

Steriade, M. (2005). Cellular substrates of brain rhythms. *Electroencephalography: Basic principles, clinical applications, and related fields, 5*, 31–83.

Swann, C., Moran, A., & Piggott, D. (2015). Defining elite athletes: issues in the study of expert performance in sport psychology. *Psychology of Sport and Exercise, 16*(Part 1), 3–14. https://doi.org/10.1016/j.psychsport.2014.07.004.

Thibault, R. T., & Raz, A. (2017). The psychology of neurofeedback: clinical intervention even if applied placebo. *American Psychologist, 72*(7), 679.

Tsai, L. L., Young, H. Y., Hsieh, S., & Lee, C. S. (2005). Impairment of error monitoring following sleep deprivation. *Sleep, 28*(6), 707–713.

Vernon, D. (2005). Can neurofeedback training enhance performance? An evaluation of the evidence with implications for future research. *Applied Psychophysiology and Biofeedback, 30*(4), 347–364.

Vernon, D., Egner, T., Cooper, N., Compton, T., Neilands, C., Sheri, A., & Gruzelier, J. H. (2003). The effect of training distinct neurofeedback protocols on aspects of cognitive performance. *International Journal of Psychophysiology, 47*(1), 75–85.

Voss, M. W., Kramer, A. F., Basak, C., Prakash, R. S., & Roberts, B. (2010). Are expert athletes 'expert' in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Applied Cognitive Psychology, 24*(6), 812–826. https://doi.org/10.1002/acp.1588.

Wang, J. R., & Hsieh, S. (2013). Neurofeedback training improves attention and working memory performance. *Clinical Neurophysiology, 124*(12), 2406–2420. https://doi.org/10.1016/j.clinph.2013.05.020.

Woods, D. L., Wyma, J. M., Yund, E. W., Herron, T. J., & Reed, B. (2015). Age-related slowing of response selection and production in a visual choice reaction time task. *Frontiers in Human Neuroscience, 9*, 193. https://doi.org/10.3389/fnhum.2015.00193.

Xiang, M. Q., Hou, X. H., Liao, B. G., Liao, J. W., & Hu, M. (2018). The effect of neurofeedback training for sport performance in athletes: a meta-analysis. *Psychology of Sport and Exercise, 36*, 114–122. https://doi.org/10.1016/j.psychsport.2018.02.004.

Yang, P., Li, I.-T., & Liu, T. L. (2018). Electroencephalogram neurofeedback treatment for Taiwanese children with attention deficit hyperactivity disorder. *Neuropsychiatry (London), 8*(1), 146–154.

Article 3

Authors: Arash Mirifar, Andreas Keil, Jürgen Beckmann, & Felix Ehrlenspiel

Title: Neurofeedback and neural self-regulation: Evidence and Challenges

Summary:

The current theoretical and empirical concerns about NFT include: 1) whether the concept of homeostasis is suited for explaining how NFT tunes brain waves (e.g. Reiner et al., 2018), 2) the lack of understanding of the neural mechanisms thought to underlie NFT, and 3) consequently, a lack of understanding of the NFT process and of mechanisms negatively influence expectations of researchers and practitioners about intervention outcomes. This paper proposed a psychophysiological model that explain the underlying mechanisms of NFT in response to the current debate. To address the debate about the generally accepted concept of homeostasis as the bases of NFT, a four-stage model of NFT was developed based on allostasis (Sterling, 2018), which explains how NFT optimizes the self-regulation of brain states. Regarding the neural mechanisms underlying NFT, research investigating in these mechanisms – which may comprise structural and functional plasticity across different levels of analysis – were reviewed and linked to the allostasis four-stage model. Thirdly, with respect to the uncertainty about the mechanisms and expected outcomes, by applying the model, I identify two differences between expected outcomes for clinical and non-clinical applications. Thus, the current understanding of neurophysiological mechanisms underlying NFT that is linked to my allostasis four-stage model of NFT should enable researchers and practitioners to improve the design of their interventions and to help them to understand and interpret their outcomes. The linkage also allows people in the field to address neural efficiency, a further theoretical issue that is still not fully understood.

Contribution:

Arash Mirifar was the principal investigator and first author of the submitted manuscript. He developed the idea for the perspective article and coordinated searching and collecting the relevant literature. The allostasis four-stage model of NFT was developed by Arash Mirifar and Felix Ehrlenspiel. Arash Mirifar wrote the paper, and all co-authors reviewed and edited the manuscript.

Neurofeedback and neural self-regulation: Evidence and Challenges

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Abstract

Interest in Neurofeedback Training (NFT) is constantly growing: more and more review papers are being published which highlight the current understanding of NFT, the applications of which have been extended from clinical uses to performance enhancement. In addition, the development of off-the-shelf technical devices even allow NFT to be performed at home. However, this development has also driven a critical debate about mechanisms (e.g., is it only a placebo?) and expected outcomes (e.g., sustained or adaptive?). Developments in the understanding of psychophysiological regulation have cast doubts on the validity of control systems theory, which is the principal framework underlying NFT. This article addresses the theoretical and empirical concerns with NFT and proposes a psychophysiological framework underlying NFT to shed light on current debates as well as to offer solutions. We are developing a model for learning self-regulation concerned with acquiring self-regulation via various techniques. Researchers and practitioners in these areas will gain an understanding helpful in providing a better rationale for NFT interventions. This model, also, identifies boundaries for what changes can be expected from a neurofeedback intervention and propose a time frame for such changes.

Keywords: Neurofeedback training, self-regulation, allostasis framework, psychophysiological regulation.

Introduction

The study of Neurofeedback (NF) began with initial explorations in the 1960s which showed that both humans and animals could acquire the ability to alter their electroencephalographic (EEG) signals in real time when given appropriate instructions and suitable feedback (see, e.g., Kamiya, 1962; Wyrwicka & Sterman, 1968). In the half century following these early observations, Neurofeedback Training (NFT) has been applied as a psychophysiological procedure to induce the ability to self-regulate specific characteristics of the EEG. Today, the available empirical evidence suggests that NFT is the most widely used technique for inducing changes in brain activity through self-regulation. Mounting evidence also showes that NFT prompts measurable clinical and performance benefits (e.g., see the reviews by Arns, de Ridder, Strehl, Breteler, & Coenen, 2009; Coben, Linden, & Myers, 2010; J. H. Gruzelier, 2014a; Moore, 2000). However, NFT has not escaped criticism from researchers, and the current discussion revolves around three issues: First, the theoretical framework of NFT has come into question, and concerns have been raised regarding whether the concept of homeostasis is really suitable for explaining how NFT tunes brain waves (e.g., Reiner, Gruzelier, Bamidis, & Auer, 2018). A second issue relates to the understanding of the neural mechanisms thought to underlie NFT. Although extensive research has shown positive behavioral outcomes for NFT, this is in stark contrast to the fact that the neural mechanisms underlying NFT – which likely comprise structural and functional plasticity across different levels of analysis – are still poorly understood. Partly reflecting this lack of understanding, several authors have also suggested that the effects of NFT may simply be due to placebo effects (Schabus, 2017; Thibault, Lifshitz, & Raz, 2016; Thibault & Raz, 2017). Thirdly, the lack of understanding about NFT's mechanisms on a model and a neural level has negatively impacted the understanding of the NFT process and, subsequently, expectations about outcomes. For example, there is an on-going discussion among researchers of whether one should expect sustained changes in resting or baseline brain activity across the sessions of an NFT intervention (see, e.g., Schabus, 2018; Witte, Kober, & Wood, 2018).

The present paper has three aims. First, we seek to develop a theoretical framework of NFT based on the current understanding of psychophysiological regulation that, in turn, will allow for a better understanding of the neurophysiological mechanisms of NFT. We start by outlining various concepts of physiological regulation, including homeostasis and control theory. Learning control or regulation involves operant conditioning, which is also used to acquire voluntary control or self-regulation of (neuro-) physiological states. Whereas more traditional control approaches have difficulty in explaining how learning and experience shape physiological regulation, we are proposing a framework based on the concept of allostasis that lets us understand how regulation is acquired and how self-regulation is exerted. Second, we will review the research into the neural mechanisms underlying self-regulation and NF and intend to relate it to the aforementioned framework. Third, we will discuss the outstanding issues regarding expected outcomes of NFT and provide ideas for how our framework might aid in solving these issues.

A psycho-physiological framework of Neurofeedback

NFT aims to enable a person to self-regulate physiological functions of the brain such as electrocortical activity. The current understanding of this self-regulation is based on an understanding of the tenets of psychophysiological regulation, which is under the control of the central nervous system (CNS) and the peripheral nervous system (PNS), the latter comprising the somatic nervous system (SNS) and the autonomic nervous system (ANS; J. H. Gruzelier & Egner, 2004). Since the time of Claude Bernard, it has been believed that physiological regulation encompasses various processes which all seek to maintain an organism in a stable (internal) state by detecting and countering fluctuations in or perturbations to the state of the organism. More recently, the idea of allostasis - assuming a more flexible, adaptive regulation - has been recognized in addition to the role of anticipatory regulation.

Homeostasis and the negative feedback loop

In 1929, Walter Cannon expanded on Bernard's ideas and introduced the term of homeostasis. This term refers to the processes and mechanisms aimed at maintaining not only a stable but also an optimal physiological state of the organism. Cannon was also the first to use negative feedback to explain how homeostasis functions (see Figure 1): A physiological process rectifies the function due to feedback (information) connecting sensors to effectors, causing the system to re-set to pre-perturbation levels (Ramsay & Woods, 2014). For example, the thermoregulatory system tries to maintain a constant level of core body temperature. If, in case of abrupt heat loss, low core temperature (hypothermia) is detected by thermoceptors, the system evokes a shivering response to raise body temperature to an optimal level by muscular activity.

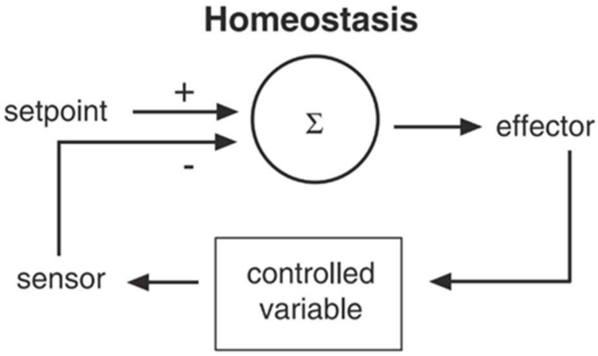


Fig 1. Homeostasis. What stands out in this model is the general pattern of maintaining a controlled parameter constant by recognizing its divergence from a “set-point” and then transferring this information to correct the error (taken from Sterling, 2012).

The proposed negative feedback loop within homeostasis was later more formally modelled within control systems theory (Wiener, 2019). It has been argued that all systems, "living and mechanical, are both information and feedback control systems" (Shinners, 1998, p. 6). Control is defined as "[directing] the behavior of (a person or animal)" or "[causing] (something) to act or function in a certain way" (Elbert, Rockstroh, Lutzenberger, & Birbaumer, 2012, p. 277). Thus, control can be considered a directing authority reliably regulating an outcome and verifying that the actual outcome matches the one intended. A control system can then be considered to be any configuration of materials organized such that a specific feature of the configuration is maintained within predefined limits. Simple control systems can be described or schematized in terms of the flow of messages through system components, i.e., communication within the system. As depicted in Figure 2, this system applies to a wide range of processes, so the concrete characteristics of the system are not specified. Rather, the focus is on the transformation of information as it flows through the system and on certain specific effects that information has on the system's output. A controller adjusts the system’s behavior according to the real-time comparison between the output sensor and the input reference value or set-point (±) in order to reduce the measured error to zero. One familiar example of a control system is the thermostat on a heater, which compares the current temperature to a set reference and then, e.g., turns the heater on or off (Gopal, 2002). Similarly, the regulation of body temperature around the set-point of 37° can be modelled within control systems theory (e.g., Hensel, 1981).

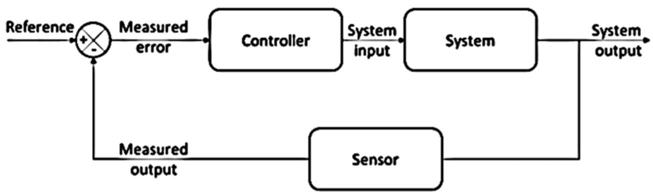


Fig 2. Basic control theory model (adapted version from LeBlanc & Coughanowr, 2008). This model is a closed-loop system, where the output is sent back, as feedback, to the input to regulate the system.

Learning from reward and punishment

In physiological regulation, beyond the hard-wired phylogenetically acquired associations (Dworkin, 1986), control over CNS and PNS functions can be acquired through instrumental learning, which is also referred to as operant conditioning. In this type of learning, the likelihood that a behavior or response is shown depends on contingencies experienced in the past. Success (reward) and failure (punishment) act to reinforce or suppress the behavior. For example, when someone is improving voluntary control of their free throw in basketball, seeing the shot go through the basket (success) serves as a reward, and seeing it miss (failure) serves as a punishment. Consequently, success (reward) and failure (punishment) in the preceding example respectively act to reinforce or suppress the behavior (i.e., throwing the ball with the same style into the basket) in each iteration or trial. For example, in terms of physiological regulation, the increase in heart rate before a 100m sprint will be associated with higher success, in turn leading to a higher likelihood of an increase in heart rate before the next event.

The elements of feedback consist of the association between a) responses, b) contingent rewards or punishments, and c) knowledge of outcomes. Furthermore, although this feedback is generally automatic, the voluntary control or self-regulation of physiological states requires the perception of this feedback. If the learner in the basketball example was blindfolded and the outcome thus unknown, then no learning would occur (N. E. Miller, 1978). Indeed, most people are unable to perceive certain physiological responses such as current blood pressure, which is analogous to a blindfolded beginner trying to learn to shoot baskets. External measurement devices that index a biological process in real time can "remove the blindfold" by supplying appropriate feedback, known as biofeedback – thus allowing learning of self-regulation of physiological states.

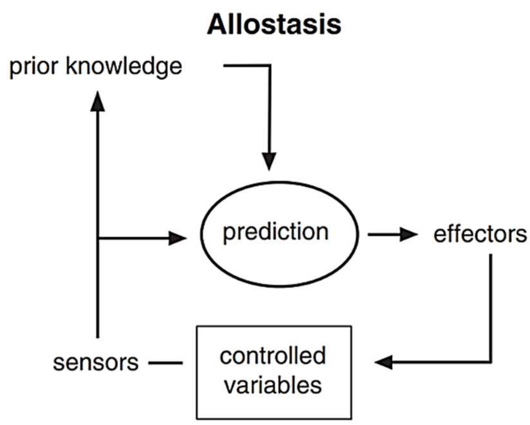
Self-regulation through bio-feedback

The mechanisms of physiological regulation are generally “automatic”, i.e., beyond human conscious awareness or voluntary control, yet they seek this control or self-regulation of their physiological states. Self-regulation refers to the manner of managing one's own thoughts, feelings, and behaviors to reach certain goals (De Ridder & De Wit, 2006), and physiological self-regulation can be considered a sub-process. Biofeedback –a process that involves receiving information (feedback) about the body or self (bio, Andrasik & Rime, 2007)– is traditionally understood to rely on the principles of physiological regulation just laid out: closed-loop feedback and operant conditioning (see e.g. J. H. Gruzelier, 2014c; Pandria, Kovatsi, Vivas, & Bamidis, 2018; Ros, Baars, Lanius, & Vuilleumier, 2014).

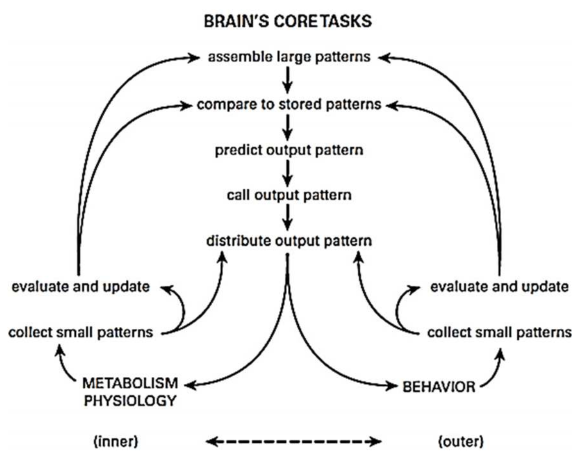
A biological system is constantly fluctuating. In the context of biofeedback, a physiological process is considered well-controlled when it can be shifted from an undesirable or unhealthy state to a desired or healthy state, while minimizing random variations, and nearly in real time. An unregulated physiological process is one which is in an abnormal state and/or cannot be changed, has too much random variation, and/or changes too slowly or too rapidly (Mulholland, 1984). The concept of biofeedback is to use operant principles to shape the regulatory processes of these fluctuations. Biological functions are not only fed back, but fluctuations in the desired direction are also reinforced by setting appropriate contingencies or instructions. Today, a wide spectrum of physiological signals are used for feedback, including the brain's activity (neurofeedback). Neurofeedback Training (NFT) has been defined as a non-invasive brain stimulation technique which trains individuals to modulate their own brain activity and drive it towards functionally desirable states (J. H. Gruzelier, 2014b). The most common NFT is to feedback electrical activity of the cortex via EEG-NFT, in which the band power or amplitude of a specific frequency range of the EEG being reinforced or suppressed. Framing NFT within homeostasis, this can be understood as a therapist providing an (external) set-point to which the current state is compared. Deviation from this set-point is fed back via the feedback signal, and the state of the system is subsequently regulated in the direction of the set-point.

Psychophysiological regulation – from homeostasis to allostasis

A more recent development in the study of physiological regulation has been the widespread recognition that homeostasis, and especially negative feedback, do not completely explain physiological regulation. One initial problem is that physiological systems lack a rigid set-point for regulation, and the state of the system may indeed be stable but far from fixed or constant. Rather, it is assumed that physiological systems fluctuate adaptively according to the demands of the environment or the organism (Ramsay & Woods, 2014). A second problem is that homeostasis is considered to rely on a reflexive response, in which a perturbation is being reacted to. However, it is clear that physiological regulation also relies on anticipatory responses (Ramsay & Woods, 2014). For example, with respect to thermoregulation, it has been shown that thermosensors on the skin produce a feedforward signal of disturbance in ambient heat which eventually leads to preventive cold-defense behavior like shivering even before the core temperature drops (Kanosue, Crawshaw, Nagashima, & Yoda, 2010). However, this anticipatory response further necessitates a learning process – a third aspect that is not considered within the concept of homeostasis. "The conclusion seems almost inescapable: the central nervous system (CNS) anticipates present and future needs on the basis of past experience. By having successfully corrected errors, the CNS learns how to prevent them" Somjen (1992, P 184). Figure 3 (A and B) illustrates the main characteristics of the model and the proce)ss of regulation based on allostasis.



A)



B)

Fig 3. A) Allostasis model (taken from Sterling, 2018). This model describes a mechanism in which the brain merges sensory data with previous knowledge to predict modification likely to be required. [….] B) Predictive regulation (allostasis). Adapting internal states of the body (bottom left) with external demands is a crucial regulatory task of the brain. [….] What is striking in this model is that the brain, before deciding on a course of action, likens larger input patterns to stored patterns to obtain historical background (what happened previously?).

In its original form, allostasis differs from homeostasis in that the level of a requisite parameter (the set-point) can vary between situations (i.e., there is no fixed set-point). Whereas homeostasis is based on stability (stasis) via constancy (homeo), allostasis is based on achieving stability (stasis) through change (allo; Gerdes, Gerdes, Lee, & H Tegeler, 2013). Thus, allostasis is described as the process of achieving stability through the adaptive adjustment of the internal milieu to meet perceived and anticipated (new) demands (Zsoldos & Ebmeier, 2016). The basic configuration of a system-maintaining state can still be presumed to be based on homeostasis, whereas the configuration of a system-changing output is based on goal-setting or allostasis (Collura, 2014, p. 48). The nature of this interaction can be seen in Figure 4. Allostasis enables an organism to adaptively respond to its physical state (e.g., awake and asleep) and to cope with its physiological state and external demands (e.g. hunger, temperature extremes , and psychosocial stress; McEwen, 2016; Sterling, 2012). Importantly, in allostasis, the necessity of "set-points" and other boundaries of control which might alter in response to potential environmental conditions are anticipated (McEwen, 2016). Thus, previous experience (i.e., learning) is incorporated into the control process, putting the system into an altered, an "allostatic state". With this in mind, we can say that a person may benefit from earlier experiences in order to properly anticipate later challenges to the internal milieu (Sterling, 2012; Sterling & Eyer, 1988). Readers interested in allostasis as a model of predictive regulation are referred to the papers by Sterling (Sterling, 2012, 2018).

First conclusion - allostasis as a framework for understanding NFT

The concept of homeostasis or classic control system theory have long been thought to account for the control of a system's physiological states and have subsequently been supposed to also underlie the learning of physiological self-regulation through biofeedback. However, it has become clear that homeostasis, at least as understood by control system theory, is not able to explain how control is acquired and how experience or the goals of the system shape regulation. Yet this is paramount for an understanding of the mechanisms of biofeedback in general, and of neurofeedback in particular. We therefore propose to frame NFT within the concept of allostasis.

In this framework (see figure 4), until an initial (current) set-point is valid, a system based on homeostasis (grey box) maintains its stability, meaning a trade-off between demand(s) and the current internal state. For example, during a brisk walk, heart rate is kept at roughly 100 bpm, with occasional fluctuations around this set-point. However, when there is a new demand due to new conditions, then a system founded on allostasis – by applying prior knowledge – introduces a new set-point in accordance with the new conditions. Based on the model that Sterling (2015, 2018) developed, when the brain perceives new demands, the information is evaluated and compared to the stored pattern. If a difference between this information and existing data and patterns is found, then the memory is updated. These perceptions and evaluations lead the brain to predict the internal and external state of the body and its future output. Following these predictions, the brain determines an efficient trade-off between demands to help the body remain in balance. Returning to the above example (i.e., a brisk walk), seeing a steep incline ahead leads to an adaptive change in the heart rate and a new set-point of 130 bpm. The system tries to maintain this new set-point (through homeostasis) until a new demand is encountered or anticipated. How, then, to relate these processes to NFT?

Importantly, the brain plays two roles during NFT: as an effector and as a regulator. During biofeedback, regulation of the functions of an effector (defined as an organ or cell that acts in response to a stimulus), such as the heart, lungs, or sweat glands, is acquired by first measuring and then feeding back activity of this effector. Additionally, the autonomic functions of the brain are in charge of this regulation, e.g., rhythmic control of the heart rate or of respiration rate, which leads to maintaining a balance in the body. Thus, in NFT, the brain plays two roles, first as a regulator of the body (and itself), which might occur by perceiving the error signal(s) and sending corrective information for regulation, and, secondly and simultaneously, as an organ or effector, which may occur by responding to the corrective information by up- and/or down-regulating brain activity.

This framework allows to distinguish two different time scales of adaptations that relate to within-session and between-session changes. Regarding the immediate, short term adaptations, the framework proposes that, during an NFT session, the system tends to regulate based on an allostatic state by reinforcing fluctuations in brain activity that follow a desired direction. This reinforcement can be understood as an external demand leading to an adaptive change of set-point. Once an NFT session is over, the system should adapt and return from its allostatic state, matching the new (or no) demand (as an example see Kober et al., 2015).

In the lab during an NFT session, in the initial stages the regulation process consists of a) ***p**erception*, and b) ***a**daptation* (PA). A new set-point is introduced into the system externally (by a therapist), and the brain, as the regulator, perceives the error signal(s) and then, as an effector response to corrective information, by modifying its function (i.e., adaptation), which, in the case of EEG-NFT, occurs by up and/or down regulation of a trained frequency or frequencies. In this step, when a new set-point is defined for the system, the stability of the system's neuro-physiological states is based on the homeostasis framework (this step is shown in the grey box in Figure 4). Gradually, the brain - as the regulator - can ***p**redict* the outcome based on the error signal(s), corrective information, and the resulting adaptation(s). The regulation process develops to PPA accordingly.

Regarding long-term or even permanent adaptations, NFT can be conceived of as optimizing neuro-physiological regulation to meet new demands in four stages. We have already explained the three stages of the regulation process that might occur by NFT under laboratory conditions as PPA. However, a permanent adaptation after the intervention process has ended might occur if the brain, as regulator, could determine a suitable set-point with respect to the internal and/or external-state of the body and its future output. Thus, the PPA model requires further development in the form of an additional step that leads the brain as the regulator after its a) ***p****erception*, b) ***p****rediction*, to c) ***d****etermining* an efficient trade-off between demands to help the body remain in balance, and finally d) as an effector ***a****dapting* its function to meet the new demands (PPDA). In this paper, the name "allostasis four-stage model of NFT" will be used to address the aforementioned stage for neurophysiological regulation and adaptation.

Overall, this paper strengthens the idea that, in the initial stages of NFT, the variations in a trained frequency are assumed to be random, without any volitional control from participants, yet meeting the set-point. It would then be possible for the brain, by connecting the reward to some specific physical or mental state, to gradually predict the next reward, which is the basis of associative or operant learning. Later, when NFT is over, based on the associative learning that is formed and developed, a participant might, outside of lab conditions and without a need for feedback, be able to predict the internal physical and mental states, external demands, and future outcome(s). Finally, within and across NFT sessions, if the brain consistently adapts to new set-points, it can be expected that, in the future and as part of its experience and learning, the brain will more appropriately and flexibly deal with a new set-point because of its flexibility in coping (adaptation) with new demands and due to having applied prior knowledge (experience). The interaction of these stages (i.e., PPDA) should help the participants to later regulate their behavior more easily and quickly in a similar situation.

Findings from previous studies (e.g., Kamiya, 1962) of NFT mechanisms focus on the participants' ability to better a) ***p****erceive* the current mental state, b) ***p****redict* whether they are in the required mental state c) ***d****etermine* a set-point which meets the required demand, and d) quickly ***a****dapt* brain activities to the desired ("set") state. These four stages (PPDA) are incorporated into our allostasis four-stage NFT model.

In a seminal study of NFT, Joe Kamiya first made the participants aware of alpha activity (frequency bursts in range of 8–12 Hz) and eventually found that participants could identify alpha activity in the absence of feedback. This means that providing feedback on a specific mental state to participants can help develop their perception of that specific mental state. Afterwards, most participants were able to voluntarily increase the incidence of the alpha rhythm following the researcher's request, and they reported the experience of the so-called ''alpha state'' as peaceful and relaxing (J. H. Gruzelier & Egner, 2005): this part of the experiment confirms that the ability of participants to deal with a new demand can be developed and improved by NFT. Such regulation can best be explained within the framework of allostasis: Brain activity not only fluctuated around a given set-point ("homeostasis") but participants were also able to change the set-point upon request and based on their experience ("allostasis"). A broader perspective was adopted by Sorger, Kamp, Weiskopf, Peters, and Goebel (2018), who showed that a protocol combining mental strategies and continuous feedback of their BOLD signal level (rtfMRI NFT) further improved the ability of participants to learn self-regulation. Participants were instructed to consecutively self-regulate the level of regional brain activation to reach 30%, 60% or 90% of their maximal capacity by implementing a selected activation strategy. The task was conducting a mental task, such as inner speech, in concomitance with modulation strategies (e.g., applying different speech rates). Most of the participants gradually showed the ability to self-regulate so as to change the regional brain activation in at least two of the target levels even in the absence of NF (Sorger et al., 2018).

Having discussed the role of homeostasis and allostasis on physiological regulation, it may be useful to conceive of the brain as a complex system in which various regulators recalibrate a given system's set-point (goal state) in a manner conforming with existing or anticipated demands. In this framework, NFT can be thought of as a procedure for establishing and enforcing additional goal states or set-points. NFT for the improvement of self-regulation involves learning relations between demands and set-points ("perception and prediction") by learning to apply collected patterns (experience), determine efficient set-points, and to quickly adapt brain activity to the desired ("set") state. Based on the allostasis four-stage model of NFT, the structural and functional plasticity/changes which are the expected consequences of NFT can now be better explained. When the brain (as an effector) adapts to new set-points, this adaptation leads to structural plasticity. When the brain (as a regulator) is involved in perception and prediction by applying prior knowledge gained through NFT, functional plasticity develops by refining and improving neural networks. For example, in the case of emotional regulation, improved interaction should take place between the areas in the brain involved in emotional perception, evaluation, regulation, and supervision, such as the amygdala and the dorsolateral prefrontal cortex (DLPFC). The following sections present and discuss the theoretical framework around neural plasticity and the evidence regarding its development through NFT.

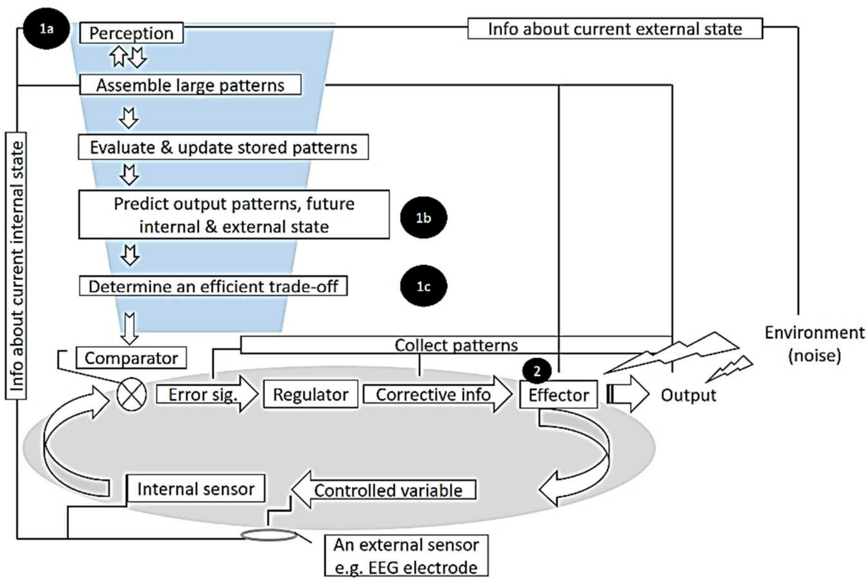


Fig 4. Allostasis four-stage NFT model for neurophysiological regulation and adaptation. 1) Brain as a regulator: A: Perceive (current internal and external state) B: Predict (output patterns, future internal & external state) C: Regulate (determine an efficient trade-off or set-point). 2) Brain as an effector: Adapt (respond efficiently and flexibly to demands).

Neural mechanisms underlying neurofeedback

Among the substantial research efforts devoted to the application of NF, there are very few investigations into the neural changes accompanying NF interventions (Bluschke, Broschwitz, Kohl, Roessner, & Beste, 2016). Neural plasticity is a broad term and is often applied to a wide range of processes, by means of which neurons (but also glia or blood vessels) change in form (structure) and/or function in response to experience, including changes in the environment or damage to the brain itself (Kaas, 2001, p. 10542). Thus far, based on the allostasis four-stage model of NFT, we have argued that, when training the brain during NFT sessions to adapt to new set-points, these adaptations might lead to different types of structural plasticity. Moreover, we argue that functional plasticity may develop during NFT when the brain perceives and predicts changes to the internal organs and the environment by applying its previous knowledge to more efficiently determine a new set-point.

Structural plasticity

Adaptive changes in brain structure in response to internal (e.g., learning) and/or external (e.g., changes in the environment) challenges, which is assumed as a result of physiological regulation, can be observed in the activity of the synapses, the activity of neuromodulators (neurotransmitters), and in microstructural changes of the neurons and their sheaths (E. J. Cohen, Quarta, Bravi, Granato, & Minciacchi, 2017). In the case of NFT, structural plasticity would be supported by findings of neural change following intervention: For example, NFT may prompt alteration of the neuron firing rate.

Synaptic modification

Neuronal activity is itself a key physiological factor which is subject to both homeostatic and allostatic regulation. In order to attain a state in which they can form and maintain constant activity patterns throughout an organism's life, billions of neurons wire themselves into intricate networks during brain network development. These circuits are not static, but rather constantly adapt to enable organisms to store information and modify their behavior in a changing environment (Turrigiano, 2012). One major mechanism mediating these adaptive network dynamics is represented by the synaptic currents transferred between neurons (Sanei & Chambers, 2007). For example, when the action potential of neuron A arrives at the axon terminating at a chemical synapse, a chemical signal (neurotransmitter) is secreted into the synaptic cleft and received by receptors sitting on the membrane of the dendrite of the receiving neuron. Upon transmitter binding, an ion channel opens allowing ions to flow into the cell and change the properties of neuron B, which can be measured as an Excitatory or Inhibitory Postsynaptic Potential (EPSP or IPSP) at the soma of the receiving neuron. The strength of an excitatory synaptic connection can be quantified by the amplitude of the EPSP. Sufficient excitation of neuron B through temporal or spatial summation of EPSPs prompts an action potential in neuron B. Importantly, EPSP and IPSP strengthen or weaken over time in response to changes in the temporal rate and changes in spatial and temporal patterns of their engagement. Together, many processes prompting changes in synaptic processing are broadly referred to as synaptic plasticity, which has been extensively discussed as a potential basis of learning (Gerstner, 2011). Most contemporary conceptions of synaptic changes and learning build upon the principles first proposed by Donald Hebb (1949).

Hebb (1949) theorized that, when the activity in a presynaptic neuron frequently induced the firing of a postsynaptic neuron, a long term alteration of the synaptic structure results, so that later activities of the presynaptic neuron have a high chance of exciting the postsynaptic neuron, or more compactly stated: “neurons that fire together wire together” (Markram, Gerstner, & Sjöström, 2011). The existing literature on associative learning (of which classical and operant conditioning are two major types) holds that, in associative synaptic plasticity, concurrent or rapid consecutive activation of two synaptically joined neurons result in a modification in the strength of synapses binding them. Synaptic plasticity has been suggested as a foundation for acquiring knowledge and memory (Feldman, 2012). Long-term potentiation (LTP) is a candidate mechanism for explaining the processes underlying associative learning (Sitaram et al., 2017), meaning that, when synapses undergo LTP, they can more effectively depolarize the postsynaptic neurons, which increases the probability that they will undergo further LTP—leading to unconstrained synaptic strengthening (Turrigiano, 2012). Recent studies have focused on a form of LTP called spike timing-dependent plasticity (STDP). Based on STDP, an alteration in synaptic transmission, which takes place over milliseconds, happens due to adaptations in the timing of weak and strong synaptic inputs. For some inputs, transmission rises due to a presynaptic response which generates a stronger postsynaptic response. However, in other cases, the transmission reduces postsynaptic responses. In essence, STDP is an asymmetric function that relies on the progression of firing times of presynaptic and postsynaptic neurons (Sitaram et al., 2017).

NFT could also be framed within Hebbian forms of plasticity, such as firing rate and synchronization (see, e.g. Ossadtchi, Shamaeva, Okorokova, Moiseeva, & Lebedev, 2017). Using intracranial recordings—not susceptible to some of the problems associated with measuring neural mass activity through scalp, skull, and cerebrospinal fluid, as is the case in EEG—animal studies have shed insights on the neuronal basis of learning as a result of NFT. For example, during neural operant conditioning in experimental animals, researchers monitored the activity of two adjacent neurons and found that, if a reward is given to a monkey when only one of the neurons is firing, the firing rate of only that neuron would instantly rise, whereas the activity of the nearby neuron did not vary (Fetz, 1969). Furthermore, if a monkey received a reward as the firing rate decreased, the firing rate continued to decrease (thus, the ability to reduce the firing rate was “increased” by reinforcement). In a study with rats, Arduin, Fregnac, Shulz, and Ego-Stengel (2013) recorded the activities of neurons in the motor cortical area. The aim was to monitor and control the neuronal activity in the motor cortical area by using a linear actuator connected to a water bottle. To obtain the reward (i.e., water), the rats had to maintain the firing rate of a neuron above a certain level. The firing rates of conditioned neurons immediately rose after a trial had begun and, in a very short time, a bottle entered the drinking zone. Moreover, the conditioned neurons fired almost simultaneously, more often, and stronger than the adjacent neurons that were recorded at the same time close to the conditioned neurons. The authors determined that only the neurons that were rewarded (operant-conditioned) showed a significant rise in firing rate, and they also prompted pronounced modulations of firing in neighboring neurons, forming a local neural network (Arduin et al., 2013). In studies using human participants, Ossadtchi et al. (2017) for the first time investigated discrete structural characteristics of EEG patterns and showed that NFT leads to an increase in the incidence rate of spindles at the trained frequency.

To conclude, first, it is now widely accepted that cortical plasticity (either in short-, medium-, or long-term) enables the brain to flexibly adapt to change, optimizing its ability to meet environmental and behavioral demands. Such modifications could be framed within the allostatic framework where the brain (acting as the system's regulator) is highlighted as a dynamically adapting interface between the changing environment and physiological regulation and adaptation. Second, by considering the allostasis four-stage model of NFT (due to frequent adaptive response to new set-points), we have argued that NFT affects neuronal activity (through parameters such as LTP and STDP) in the short-term but is also thought to change the strength of synaptic connections (referred to as "synaptic weight"), a form of neuroplasticity which has been linked to associative learning. The following section addresses the roles of neurotransmitters in reinforcement learning (operant conditioning), and more specifically in NFT.

Neurotransmitters: interaction and modification

One conclusion frequently drawn from the research on STDP is that, if a synapse active just prior to a spike event would increase in efficacy, then a synapse that is only active after the spike would otherwise decrease efficacy. The question arises of whether the mere association of presynaptic input and postsynaptic spiking activity is sufficient to induce synaptic efficacy. One possible answer to this question has been proposed in the context of reward-mediated learning (R. Miller, 1981; Wickens, 1990). Beyond pre- and post-synaptic activity, some theoretical studies have suggested that a "third factor" might be involved in the network that enabled both the temporal and the spatial selection of specific inputs (Pawlak, Wickens, Kirkwood, & Kerr, 2010).

Theoretical and computational studies have proposed that neuromodulators represent such a third factor for selecting particular active inputs to a neuron in an active network. One of the most important neuromodulators that has been investigated is dopamine, which appears to impact timing-dependent plasticity within a number of areas of the brain (Bissiere, Humeau, & Luthi, 2003; Pawlak et al., 2010).

Dopamine neurons have a short-latency, a phasic reward signal signifying the discrepancy between existing and predicted rewards. Evidence suggests that dopamine can play an important role in addressing the issue of reward and approach behavior (Schultz, 2002). Although outside of the scope of the present review, some pertinent mechanisms will be briefly reviewed below. Readers interested in the dopaminergic effects on operant behavior are referred to the comprehensive reviews by Kringelbach and Berridge (2016). Dopamine is a mediator that links STDP to behavioral modifications by inducing plasticity at corticostriatal and cortical synapses (Gallistel & Matzel, 2013; Sitaram et al., 2017). Behavioral research in animals and humans in which dopamine transmission was experimentally restricted has specifically linked motivational effects to dopaminergic projections from the nucleus accumbens to the frontal cortex. This network appears to be crucially involved in the use of reward information for learning, maintaining, and consummatory behavior (Schultz, 2002). One prevalent hypothesis regards dopaminergic activity at the time of reward delivery as a teaching signal that results in learning about previous cues.

It has been shown that the ventroanterior midbrain – the substantia nigra and ventral tegmental area – are largely comprised of cell bodies of dopaminergic neurons. Neuroimaging studies show that the axons of these neurons project separately in a general topographic order to the striatum (the caudate nucleus and putamen), the ventral striatum including the nucleus accumbens, and many areas of the neocortex, primarily the prefrontal cortex. A smaller dopaminergic cell group localized in the hypothalamus has different functions and is not relevant to the present review paper.

Dopaminergic neurons broadly discriminate between reward and non-reward stimuli, but not between the types of stimuli providing the reward (e.g., juice versus food). In classical and operant conditioning tasks, when visual and auditory stimuli are conditioned, between 55% to 70% of dopamine neurons are activated (J. D. Miller, Sanghera, & German, 1981; Schultz, 2002). Dopamine responses occur temporally close to behavioral reactions (Nishino, Ono, Muramoto, Fukuda, & Sasaki, 1987). In early learning periods, primary rewards evoke neuronal activations. However, this activation declines progressively and is transferred to the conditioned, reward-predicting stimuli within the process of learning. Rewards and conditioned stimuli activate dopamine production during a phase of learning. When the learning is terminated, a shift in activation between unpredicted rewards and reward-predicting stimuli immediately occurs (Mirenowicz & Schultz, 1994; Romo & Schultz, 1990; Schultz, 2002).

As discussed earlier, NFT rewards neural fluctuations in a desired direction and, consequently, positively reinforces these fluctuations. Conversely, the fluctuations in an undesired direction are punished. Thus, dopaminergic signaling may play an important role in associative learning during NFT.

Evidence from animal studies suggest that NFT affects spike the activity of brainstem dopaminergic neurons. For example, Kulichenko, Fokina, and

Pavlenko (2009) reported that the EEG alpha/theta ratio changed during NFT in cats due to an increase in the alpha-band (8-13 Hz) and a decrease in the theta-band (4-8 Hz) of spectral power density in feline EEG recordings. Using invasive recordings across the same neurofeedback training, the authors observed an augmentation of the spike activity of dopaminergic neurons (Kulichenko et al., 2009). Moreover, in human studies, the effect of NFT on substantia nigra/ventral tegmental area activation was tested directly by Sulzer et al. (2013). The authors reported that only participants with veridical feedback (compared to a group with sham feedback) improved their ability to up-regulate dopaminergic signaling in the substantia nigra/ventral tegmental area complex. Feedback also prompted co-activation of other dopaminergic regions and augmented connectivity along the nigrostriatal pathway when compared to the control condition (Sulzer et al., 2013).

In addition to establishing the role of dopamine in neuroplasticity, research has highlighted an essential role for glutamateric signals. Glutamate has been recognized as the major excitatory neurotransmitter in the CNS of mammals. It is found in pyramidal neurons, which are abundant in the cerebral cortex and in several hippocampal tracts. Glutamate is, therefore, essential for all mammalian behaviors, particularly with regard to learning and memory (McEntee & Crook, 1993). Recent studies show that postsynaptic glutamate receptors can be regulated dynamically by excitatory synapses, displaying time-varying changes in synaptic efficacy as seen for example in LTP and long-term depression (LTD; Purves et al., 2001). Experimental evidence has suggested location-specific increases in glutamate and glutamine concentration when transcranial Direct Current Stimulation (tDCS) was applied during a challenging visual search task (Clark & Parasuraman, 2014). This evidence can be understood as an indirect proof for other kinds of neural stimulation techniques, such as NFT, which have changed the behavior.

In this section, we have reviewed a number of neural processes that may play a role in associative learning and may thus inform the study of NFT. A strong pre- and post-synaptic activation and dopamine release can have profound consequences on the results of learning. Based on three-factor learning theory, synaptic transmission is strengthened only in those neurons that concurrently receive inputs which code some element of an experience in the milieu and dopaminergic input relative to the reward prediction error. Therefore, due to contingent feedback, dopaminergic projections to the striatum might enable a behavior to be modified in reaction to relevant stimuli and contingent feedback. In addition, an increase in glutamatergic transmission, a major excitatory transmission of the brain, has been reported to be a consequence of neural stimulation. Overall, this evidence provides direct insights into reinforcement- and NF-learning mechanisms, meaning that synaptic changes are involved in the learning process. The section below examines the changes in gray and white matter due to NFT, another element of structural plasticity.

Gray and white matter modification

For a long time, it was widely believed that the brain, having reached adulthood, was an anatomically and physiologically static organ (van Boxtel & Gruzelier, 2014). However, evidence became available that the brain possesses self-organizing principles, which means that neural systems are modifiable networks, and training in adults can lead to changes in neural structure (Hölzel et al., 2011). These structural changes are evident in the case of self-regulation (Hölzel et al., 2011; Tang, Lu, Fan, Yang, & Posner, 2012), as well as in the acquisition of abstract information (Draganski et al., 2006), motor skills (Draganski et al., 2004), cognitive skills (Ilg et al., 2008), and physical training such as aerobics over a period of time (Colcombe et al., 2006). Regarding the nature of adaptive structural plastic changes in the neuronal circuits of the brain caused by self-regulation, neuroimaging studies have shown changes in white and gray matter are driving factors of self-regulation (e.g., here mindfulness training was applied to demonstrate structural changes in the brain, Hölzel et al., 2011; Tang et al., 2012). In NF studies, increases were also reported in fractional anisotropy in white matter pathways and grey matter volume (e.g., Ghaziri et al., 2013). It has now been established that there is an inseparable connection between the components of neural regulation, e.g., brain function and structure (Ros et al., 2014). Thus, a successful NFT which causes functional changes in the brain is expected to positively induce some structural changes in the brain. To date, however, there has been relatively little evidence supporting the notion that changes in brain activity after NFT are accompanied by microstructural changes in the white matter pathways and gray matter volume (Ghaziri et al., 2013; Hohenfeld et al., 2017; Munivenkatappa, Rajeswaran, Indira Devi, Bennet, & Upadhyay, 2014; Papoutsi et al., 2018).

This section has examined another level of neural plasticity - structural adaptive neuroplasticity - which could be caused by NFT. These changes seem to be necessary for at least a functional rewiring. It has been argued that NFT involves multiple aspects of mental functions that use multiple complex interactive networks in the brain (Gaume, Vialatte, Mora-Sánchez, Ramdani, & Vialatte; Sitaram et al., 2017), which will be discussed in the following.

Functional plasticity

Adaptive plasticity in brain function in response to internal (e.g., brain damage) and/or external (e.g., changes in the environment) demands can be observed through strengthening, weakening, adding, or pruning in the connectivity of different brain regions (E. J. Cohen et al., 2017). In the case of NFT, functional plasticity would be supported by findings of modification in the connectivity between different regions following intervention. For example, NFT may result in an altered network configuration.

Neural underpinnings of self-regulation

Recent developments in the field of neuroscience have helped expand our understanding of the neural underpinnings of self-regulation. Early examples of research on this topic addressed the possibility that the functions assumed for the supervisory attentional system (controlled processing) correspond to the prefrontal areas described by Luria (1966) as responsible for the execution and regulation of behavior (Banfield, Wyland, Macrae, Munte, & Heatherton, 2004). We will explore two key functions involved in NFT: executive functions and memory.

We have investigated data which will help determine which brain areas are involved in these functions, how these areas are implicated in the self-regulation process, and how these areas interact during NFT.

Executive function

All cognitive processes related to self-regulation, monitoring, initiation of activity, use of feedback, and more are thought to be an enveloping process of the executive functions (Cannon et al., 2007; Sohlberg & Mateer, 1989). It has long been known that various sectors of the prefrontal cortex (PFC) circuits are implicated in executive functions: the dorsolateral prefrontal cortex (DLPFC), the ventromedial prefrontal cortex (VMPFC), and the anterior cingulate cortex (ACC; Banfield et al., 2004). Thus, the mapping of anatomical connectivity patterns underlying regions of the PFC is crucial to comprehending how these regions work together to make self-regulation feasible.

The DLPFC has been demonstrated to play an important role in addressing the issue of cognitive processes, e.g., actively retaining information in working memory (Duncan & Owen, 2000), changing behavior according to task demands (MacDonald, Cohen, Stenger, & Carter, 2000) or representing past events, current goals, and future predictions (E. K. Miller, 2000). Given these issues, research suggests that activation in DLPFC is linked with behavioral self-regulation, for example the selection and initiation of actions (Banfield et al., 2004; Spence & Frith, 1999). This idea is supported by evidence that shows elevated activation in DLPFC when participants successfully engage in self-control (e.g., Hare, Camerer, & Rangel, 2009). Moreover, evidence shows that damage to the DLPFC often results in apathy as well as diminished ability to pay attention, plan, and judge. Individuals also often show diminished self-care (Dimitrov et al., 1999). However, it has been argued that the DLPFC is not exclusively responsible for the executive functions and that additional cortical and subcortical circuits need to be considered, e.g., the neural circuit that includes the posterior parietal cortex, the head of the caudate nucleus, or the dorsomedial thalamic nucleus (Siddiqui, Chatterjee, Kumar, Siddiqui, & Goyal, 2008).

The VMPFC demarcation in neuroimaging studies show its strong interconnection with the limbic structures involved in emotional processing, and the orbitofrontal cortex (OFC), which is a part of VPFC, has been suggested as one contributor to emotional processing (Pandya & Barnes, 1987), reward and inhibition processes, real-life decision making (Hernandez, Denburg, & Tranel, 2009; Rolls, 2000), self-awareness (Stuss, 1991; Stuss & Levine, 2002), and strategic regulation (Levine et al., 1998; E. K. Miller & Cohen, 2001). Lesion studies in monkeys and humans have suggested that OFC lesions result in poor self-regulation and, similarly, in personality changes such as indifference, impaired social judgment, impaired pragmatics and social responsiveness, and the inability to associate situations with personal affective markers (Damasio & Van Hoesen, 1983; Malloy, Bihrle, Duffy, & Cimino, 1993; Raine & Yang, 2006). Surprisingly, individuals with a lesion of the OFC may nevertheless be able to gain appropriate self-insight in certain circumstances and be able to judge whether a behavior is moral or immoral, acceptable or unacceptable, but they are unable to act on this knowledge in order to adjust or guide their own behavior appropriately (Beer, 2011). It has been argued that OFC is associated with reward monitoring and processing; reward-related responses can be heavily dependent on the task in which the subject is engaged (Luk & Wallis, 2013). In this regard, OFC neurons with consistent valence encoding might have an impact on the prediction of feedback, depending on the content of stimuli. Finally, the OFC is postulated to convey information concerning the value of likely rewards. Such knowledge is crucial for associative learning which builds upon the similarities between the expected and the obtained reward for causing instructive error signals (Takahashi et al., 2011).

The ACC is a specialized medial prefrontal region that consistently interacts with the PFC in monitoring and guiding behavior (Gehring & Knight, 2000b) and is thought to be part of a circuit that regulates both cognitive and emotional processing. The ACC is functionally split into ventral (affective) and dorsal (cognitive) regions, which have distinct cytoarchitectures, connectivities, and functions (Vogt, Vogt, Farber, & Bush, 2005). Located between the neocortex and the limbic system, the ACC is well positioned to serve as an interface between cognition and emotion. This region contains spindle-shaped neurons allowing for widespread connections to other brain areas. The AC areas have extensive connections with the insula, PFC, amygdala, hypothalamus, and brainstem. Via these projections, the ACC controls sympathetic and parasympathetic functions (Hurley, Herbert, Moga, & Saper, 1991; Ter Horst, Hautvast, De Jongste, & Korf, 1996; Terreberry & Neafsey, 1987; Verberne & Owens, 1998). Accordingly, the ACC is strongly involved in issues of self-regulation (Awh & Gehring, 1999; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Carter et al., 2000; Posner & Rothbart, 1998). Research has established a role for the ACC in decision making and behavior monitoring (Bush et al., 2002; Elliott & Dolan, 1998; Liddle, Kiehl, & Smith, 2001), reward-punishment assessment (Knutson, Westdorp, Kaiser, & Hommer, 2000), as well as initiating the selection of an appropriate novel response among several alternatives (Raichle et al., 1994), performance monitoring (MacDonald et al., 2000), action monitoring (Gehring & Knight, 2000a; Paus, 2001), detecting or processing response conflict (Gehring & Fencsik, 2001), detecting and processing errors (Carter et al., 1998; Kiehl, Liddle, & Hopfinger, 2000; Menon, Adleman, White, Glover, & Reiss, 2001), error outcome and predictability (Paulus, Hozack, Frank, & Brown, 2002), and internal cognitive control (Wyland, Kelley, Macrae, Gordon, & Heatherton, 2003). Clearly, dysfunction within the ACC can disrupt self-regulatory processes on several levels. Not surprisingly, our understanding of behavioral deficits following ACC damage is limited since is infrequently injured during closed-head trauma. However, in neuropsychological tests, patients who underwent cingulotomies demonstrated deficits on the Stroop color-naming task and showed difficulty in spontaneously generating novel responses in a design fluency task (R. A. Cohen, Kaplan, Moser, Jenkins, & Wilkinson, 1999). Neuroimaging investigations exploring the neural mechanisms behind ADHD (Bush, Valera, & Seidman, 2005) and autistic spectrum disorder

(Cherkassky, Kana, Keller, & Just, 2006) have exposed hypo activation and functional under-connectivity of the ACC, which might explain why cognitive deficiencies associated with ADHD and autistic spectrum disorder frequently seem to fall within the domain of self-regulation and executive function (Barkley, 2017).

This section, which has presented findings from cognitive neuroscience that elucidate what happens when self-regulation breaks down, focused on three different sectors of the PFC and their role in self- regulation. First, the DLPFC has been demonstrated to play a crucial role in key aspects of executive function (e.g., cognitive processes and changing behavior according to task demands) that are essential for planning behavior and maintaining regulatory goals. Second, the VMPFC shows a strong interconnection with the limbic structures involved in emotion, receiving rewards, the inhibition process, and strategic regulation. Third, the ACC, a region located between the neocortex and the limbic system, is well-positioned to serve as an interface between cognition and emotion. The ACC has been shown to be involved in monitoring signals which are required for control systems to regulate behavior. The function of memory in self-regulation will be investigated in the following.

Memory function

One further factor that must be considered when brain function and self-regulation are being investigated is the role of memory. As was pointed out earlier, working memory operations such as the maintenance and updating of relevant information is an essential and primary element for executive functions. Data from several studies suggest that successful self-regulation entails the representation of goals and goal-relevant information (Kane, Bleckley, Conway, & Engle, 2001; E. K. Miller & Cohen, 2001). Working memory may directly subserve the active mental representation of an individual's self-regulatory goals (recruited from long-term memory) and the associated means by which these goals can be attained (Hofmann, Schmeichel, & Baddeley, 2012; E. K. Miller & Cohen, 2001). Researchers have argued that, without an active representation of such goal-related information, self-regulation is directionless and bound to fail (Baumeister & Heatherton, 1996) unless individuals have fully habitualized and automatic self-regulatory routines at their disposal (Fishbach & Shah, 2006; Gollwitzer & Brandstätter, 1997).

Thus far, different regions of the brain involved in behavioral regulation have been explained, and the role of memory in self-regulation has been discussed. In the following, the empirical evidence will be reviewed to track how these regions are activated and modified during and after NFT.

Empirical evidence for functional plasticity due to NFT

Turning now to the experimental evidence on the regulation of brain functioning through NFT, preliminary evidence suggests that learning self-regulation of brain activity through NFT can lead to changes in functional connectivity. This view is supported by the hemodynamic response in different brain regions such as the dorsal ACC, the thalamus, the lateral PFC, and other regions, which have been associated with performing (voluntarily trying to control feedback from various brain signals) and/or learning NF (see Emmert et al., 2016 for review). By way of illustration, Paret et al. (2018) investigated the neural signatures of feedback monitoring and controlling when participants were provided with continuous rtfMRI NFT from the amygdala. For feedback monitoring, the researchers reported activation in the thalamus, VMPFC, ventral striatum, and rostral PFC. Feedback controlling, on the other hand, engaged the ACC, lateral PFC, and insula. Moreover, Paret et al. (2018) observed an overlap in the thalamus and ventral striatum activations, which means they are also involved in feedback controlling. Similarly, Zotev et al. (2011) showed how the functional connectivity between a single region of interest and regions that were interacting changed significantly across the rtfMRI NFT. Participants in the intervention group were provided with ongoing information about blood oxygen level dependent (BOLD) activity in the left amygdala and were instructed to raise the BOLD rtfMRI signal by contemplating positive memories. A control group was given the identical activity. However, participants received sham feedback based on the activity of the left horizontal segment of the intraparietal sulcus (HIPS), a region that is not thought to play a role in emotion regulation. A significant increase in the BOLD signal due to rtfMRI NFT at the left amygdala was reported only for the experimental group. This effect persisted during the transfer run without NF. A functional connectivity analysis of the amygdala network also revealed significant widespread correlations in a fronto-temporo-limbic network. Additionally, the authors detected six regions — the right medial frontal polar cortex, bilateral dorsomedial PFC, left ACC, and bilateral superior frontal gyrus — where the functional connectivity with the left amygdala rose substantially during the rtfMRI NFT runs and the transfer run. These activation patterns have also been observed in the case of slow cortical potentials NFT. Raised BOLD responses have been found in the dorsal anterior cingulate gyrus, the anterior insula, middle frontal gyrus, and the supplementary motor area when participants experience NFT in the form of surface-negative slow cortical potentials (increased cortical excitation), whereas positivity (decreased cortical excitation) was associated with widespread deactivations (Hinterberger et al., 2003) This has been also seen in the case of sham NFT. In a recent fMRI study by (Ninaus et al., 2013), participants thought they were receiving valid NFB but, unbeknownst to them, were instead watching a realistic video of a NFT session inside the fMRI scanner. In a passive viewing condition, participants were ordered to only watch the bar movements but to not attempt to control them. Participants in the active condition were expressly requested to control their brain activation so that the moving bar remains as high as possible –a normal task in NFB studies. When differentiating the passive with the active task conditions, the ACC, the anterior insula, the middle frontal gyrus and the supplementary motor area were strongly activated in a bilateral manner, which stresses the areas of the brain involved in supervisory control. Regarding the function of memory, it has been argued that, when participants explore different cognitive strategies in an attempt to control the NF signal, they must remember a history of behaviors over time and determine which behavior was responsible for influencing the feedback signal (Oblak, Lewis-Peacock, & Sulzer, 2017). The hippocampus is apparently involved in recalling information, particularly for episodic memories (Shirvalkar, 2009). The consolidation of the long-term memory, stored in cortical networks, results from the reactivation of the assembly due to operant conditioning. In this phase, the VMPFC and the hippocampus may work together to form schema and possibly represent semi-consolidated schemata (van Kesteren, Fernández, Norris, & Hermans, 2010). Finally, a recent meta-analysis literature review (including 12 experiments that investigated nine different target regions for a total of 175 participants and 899 NFT sessions) suggested that the anterior insula and the basal ganglia, in particular the striatum, were constantly active throughout the regulation of brain activation across the experiments. Moreover, the results of this study showed additional activations in the ACC, the dorsolateral and ventrolateral PFC, the temporo-parietal area, and the visual association areas, including the temporo-occipital junction (Emmert et al., 2016).

As mentioned above, the aim of this section has been to track the effects of NFT on the regions crucial for self-regulation. These effects could be considered as being functional plasticity in interaction with the change in the level of self-regulation. As expected, the brain regions, such as VMPFC and ACC, which are identified as playing a role in addressing executive and memory functions, regardless of trained frequency and location, showed activation during and after NFT termination. The evidence suggests that NFT enables the manipulation of neural activity in circumscribed regions in the form of trained regions and, accordingly, might drive some functional connection activities in other brain regions. The ability to enhance neural dynamics at a network level with NFT may be a better method for neural regulation than NFT involving one area. This widespread activation by NFT appears to be required for brain and behavioral regulation (Gaume et al.; Ros et al., 2014; Sitaram et al., 2017).

Second conclusion - neural mechanisms underlying NFT

We have proposed that NFT should be framed within the theoretical framework of allostasis: NFT may alter the state (set-point) of brain activity. The alterations in brain oscillatory activity and connectivity induced by NFT may be produced by structural and functional plasticity at different levels of analysis, ranging from molecular to system-level changes: NFT-based plastic changes may include synaptic modification, alterations in gray and white matter, and may also promote measurable changes taken to indicate functional plasticity. Quantifying such changes is needed in order to rigorously investigate the neural mechanisms and, ultimately, the effectiveness of NFT. Such an objective and quantitative approach may also address some concerns regarding the external and internal validity of NFT (such as Schabus, 2017; Thibault & Raz, 2017).

In the neuropsychophysiological literature, the association between self-regulation and the activation of different brain regions is discussed and, the activations and modifications of these regions are also examined in the NFT literature. Interestingly, the brain regions discussed earlier in the section on neural mechanisms underlying NF involved in neurophysiological regulation are similar to those that other researchers (such as Stephan et al., 2016) have suggested are involved in homeostasis and allostasis regulation. For example, in their analysis of neuroanatomical circuits, Stephan et al. (2016) proposed that the anterior insular cortex, ACC, subgenual cortex (SGC), and OFC play an important role in homeostasis, allostasis, and interoception. The authors argued that these regions, which they call “visceromotor areas”, are situated at the top of this circuit, embodying a generative model of (potentially different types of) viscerosensory inputs enabling a biological agent to infer current bodily states and predict future states. These visceromotor areas form the basis for allostatic predictions.

However, the research in this field is generally limited to specifying whether changes in the structures and functions of the brain lead to self-regulation and, if so, how far the concept of self-regulation can be attained, or whether participants have no control over alterations of the brain after NFT. We should bear in mind that structural and functional alterations of the brain may also happen through techniques that externally stimulate neurons (vs. NFT that internally stimulates the neurons), such as rTMS and tDCS, without volitional control on up- or down-regulation of neural activity as a consequence of learning self-regulation. Historically, the term "self-regulation" has been used to describe volitional control of one's own thoughts, feelings, and behaviors to reach certain goals. Thus, it is assumed that the alterations in the brain oscillatory activity induced by NFT should be under the volitional control of the participants after the termination of training. In the field of NFT, it has thus far been shown (e.g., by Joe Kamiya) that participants were, after the termination of NFT, able to voluntarily increase the incidence of the trained frequency (i.e., alpha waves) based on demands (e.g., a researcher’s request). However, the participants were not able to say how they produced that mental state (Thompson, 2004).

We contend that, taken together, the mechanisms underlying NFT trigger synaptic modifications which lead to a firming of neural circuitry (Davelaar, 2018; Niv, 2013; Ros et al., 2014) due to an adaptation to new set-points. These modifications (contraction and/or expansion) are required for functional changes at the neural network level, e.g., the default mode network (see, e.g., Russell-Chapin et al., 2013), and/or regions that are involved in the executive function, such as DLPFC, the region that is involved with changing behavior through incorporating past events, current goals, and future predictions.

From mechanisms to outcomes – expected effects of NFT

The aim of this paper was to develop our understanding of NFT and, subsequently, the expectations about outcomes. Thus far, we have critically examined some conceptual and methodological issues associated with adaptive physiological regulation. In general, this neuro-psycho-physiological regulation should be seen within the framework of allostasis. The effects of NFT can best be explained within the allostasis four-stage model of NFT, by (a) learning relations between demands and set-points, (b) learning to apply collected patterns (experience), (c) determining efficient set-points, and (d) quickly adapting brain activity to the desired ("set") state. Given that we have argued (in contrast to the beginning of NFT) that, when NFT is complete, adaptation likely occurs after of a perception and a prediction of new demands and the determination a new set-point which is no longer introduced to the system by the experimenter.

NFT does improve the ability for superior perception, prediction, and adaptation through developing and refining the structural and functional plasticity. When, as an effector, the brain consecutively adapts to new set-points, this leads to structural plasticity such as synaptic modification and alterations in gray and white matter. And, once the brain (as a regulator) applies prior knowledge (experience) for perception, anticipation, and adaptation, this promotes measurable changes taken to indicate functional plasticity. This theoretical framework of NFT has not previously been described, and the aim of developing it has been to provide ideas for solutions to issues currently debated with respect to NFT and the effects and mechanisms thereof. The most obvious conclusion emerging from this review is that NFT enables the system to set appropriate set-points. This ability can form on the basis of more precise perception and prediction. Meanwhile, NFT enables the system to deal and adapt more efficiently to a new set-point by applying the experience gained and developed during the training.

In the following section we want to explore how framing NFT within the allostasis four-stage model can help us to better understand the effects of NFT and how the model can resolve debated issues. We will also present predictions derived from the model that may be used to test the model.

Changes in baseline (sustained changes) or adaptive changes?

Traditionally, the effectiveness of NFT has been expected to be shown through sustained changes in the power of the trained frequency across intervention sessions, even in resting baseline measurements. That is, when a trained frequency is up-regulated the increase in the power of that frequency remains stable; conversely a reduction in the power remains stable when a trained frequency is down-regulated. By way of illustration, Zoefel, Huster, and Herrmann (2011) applied NFT to reinforce an individually-determined upper alpha frequency, ultimately to improve cognitive performance. In the course of the training sessions, they recorded a substantial linear increase in the upper alpha amplitude (Figure 5). In the final training session in both pre- and post-intervention, the alpha amplitude was higher than the very first pre- and post-intervention, respectively. Doubt has recently been cast on the validity of this continuous progression or increase as a valid marker for the effects of NFT (Witte et al., 2018). The authors argued that the nature of NFT is reflected in participants having attained the ability to (self-) regulate instantaneously. Thus, a trainee in an EEG-NFT intervention may learn to quickly regulate brain activations with less conscious cognitive effort (Witte et al., 2018), but not to constantly regulate these activations.

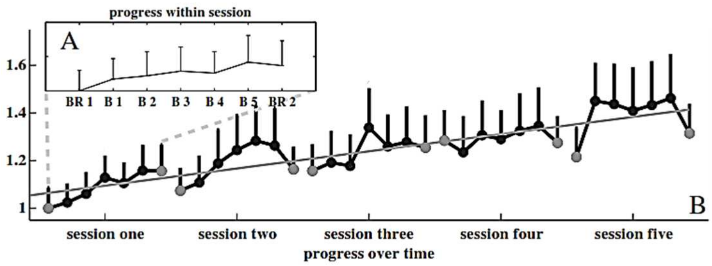


Fig 5. Progress within and across sessions; taken from (Zoefel et al., 2011)

The four-stage model of NFT can now more precisely explain these changes in the rest condition. One key assumption of allostasis is that a set-point changes as a result of demands. However, in the rest condition, which is an inherently stable condition with few variations in the environment, there are no such changing demands. Why should the set-point then change?

To answer this question, two different conditions for NFT should be considered. We assume that the aims and outcomes of NFT differ between allostatic (over)load states (e.g., clinical applications) and allostasis states (e.g., non-clinical applications). In this regard, in an allostatic (over)load state, such as in ADHD or a major depressive disorder, the brain activity appears to be dysregulated. In contrast, in an allostasis state (e.g., a performance-enhancing application), the brain activity is generally well-regulated. Accordingly, when NFT is applied, the researchers should consider the condition of the participants and the purpose of the intervention. These conditions will be explained in more detail below.

NFT to modify allostatic (over)load states (improving clinical conditions)

When NFT is applied to treat a patient, the aim is to ameliorate the symptoms and to modify brain functioning toward a healthy condition. Framed within the allostasis model, the person's brain activity is in a condition of allostatic (over)load in which brain activity is not adaptively changing according to demands (McEwen & Wingfield, 2003). Whereas, in a healthy system, changes to the set-point occur adaptively, maladaptive functioning leads to health problems. For example, it has been argued that perceptions of (chronic) stress lead to "allostatic load" in that the set-point or allostatic state is not re-set or turned off after some time. This can be illustrated briefly by continued elevated blood pressure in response to continued or repeated perceptions of stress which can lead to maladaptive changes like hypertension and subsequent atherosclerosis. Allostatic load can occur as a result of continuous demands or repeated "hits", a failure to re-set, or a failure to respond to demands at all (Sterling, 2012). The dysregulated brain activity in persons with ADHD can be seen as an allostatic (over)load. Although the elevated theta/beta ratio may be adaptive to demands in an inattentive, unfocused state, the prolonged or permanently elevated pattern is maladaptive. In such a state, e.g., Monastra (2008) has argued that theta waves predominate over the prefrontal and frontal cortex, as well as at certain midline locations, such as the vertex. Thus, in a clinical application, NFT is supposed to restore the flexibility of a system's regulator (i.e., the brain) to vary parameters of its internal milieu and match them to environmental demands by breaking down the allostatic (over)load that has caused an unhealthy condition. The breaking down of an allostatic (over)load should be considered an extra step, or a prerequisite for an unhealthy system to become healthy, as compared to what exists in non-clinical (or optimizing) applications of NFT. In clinical applications, the focus of NFT within the four-stage model thus lies on enhancing the perception of current internal and external states, the prediction of output patterns, future internal and external states, and the determination of an efficient trade-off or set-point.

NFT to increase allostasis competence (improving performance)

In non-clinical applications, e.g., to enhance the performance of athletes or artists, the system is not generally dysregulated and has flexibility to react to demands. The principal aim is, therefore, to enhance the capacity for adapting the system's state to task demands and do so as accurately and quickly as possible. Thus, based on the allostasis model the changes in brain oscillatory activity in this scenario should be limited to the training sessions and the execution time. In the rest condition, the brain functioning of the participant, as a non-patient, should not be far outside the norm. These alterations in brain oscillatory activity, e.g., during the execution time, are responses to changes in condition and, as a consequence, new demands.

Therefore, when NFT is employed to optimize performance, the aim is to change the brain's oscillatory activity only during NFT sessions and while a specific task is being executed, but not apart from these conditions. For a healthy participant (with an intact brain and without any mental disorder) who can handle daily affairs without any problems, a long-term change in brain activity and function could lead to unwanted outcomes. A protocol applied to healthy participants is generally driven by brain activity linked to an optimal performance of a desired task. For example, changes that have been reported in event-related synchronization/desynchronization studies regarding optimal and non-optimal performance of a specific task (see, e.g. Landers et al., 1991; Ring, Cooke, Kavussanu, McIntyre, & Masters, 2015). Thus, there is no need for any changes in brain oscillatory activity in other conditions, like in the resting condition. Researchers (e.g., Mirifar, Keil, Beckmann, & Ehrlenspiel, 2019) instead theorize that participants initially learn (consciously or not) to modify their brain activity according to the aim of the intervention during training sessions and then transfer this ability of flexible regulation to the execution time. The assumption that participants can learn to modify brain activity can probably be explained by a flexible and precise regulation function that can be induced by NFT and which accords with the allostasis framework. Thus, the focus of NFT within the four-stage model in non-clinical applications, lies on enhancing efficient adaptation.

In clinical applications, in contrast, researchers can expect to observe sustained changes in a trained frequency across time. That is, gradual changes in the trained frequency occur within sessions but are also sustained between sessions even under rest conditions. In non-clinical applications, however, changes in the trained frequency should only be observed during the time of training (within sessions) and at the time of task execution – when specific demands (of a task) are high. In principle, prolonged and sustained changes of trained frequencies in the resting state (between sessions) are not expected. However, there is one exception to this rule: Due to the neural efficiency induced by NFT, prolonged changes in brain activity after NFT to enhance alpha activity (7-13 Hz) should be expected.

Alpha activity is indicative of the inhibition and suppression of unnecessary or irrelevant information processing, especially during the resting state. After NFT, inhibition should generally be more evident in resting conditions. Therefore, the key outcome of non-clinical applications is instead the flexibility of the system to respond to demands and the accuracy and the rate of change – efficient adaptation.

The four-stage model of NFT predicts that NFT induces a more flexible ability to self-regulate. Thus, it would be useful if researchers were to demonstrate how flexible self-regulation by means of NFT can be with regard to volitionally alternating between up- and down-regulation of a trained frequency. In light of the expectations for an NFT outcome, the other issue that probably should be addressed is the relation between neurophysiological and behavioral changes that might occur due to NFT.

An explanation of the relation between the neurophysiological and behavioral changes induced by NFT

Another issue that remains controversial in the field of NFT is the interaction of neurophysiological- and behavioral-changes and whether neurophysiological changes are behind behavioral changes. In addition, how much do these changes depend on each other? After scrutinizing the evidence in the field of NFT, researchers (such as Micoulaud-Franchi & Fovet, 2018; Thibault & Raz, 2018) have argued that there is an ambiguous relationship between the mechanisms underlying NFT, which are: a) psychosocial, b) cognitive, and c) neurophysiological. A broader perspective on the discrepancy between neurophysiological- and behavioral-changes has recently been revealed by Tinga, de Back, and Louwerse (2019), who show that the effect sizes of neurophysiological outcomes are smaller than those of behavioral outcomes. With reference to our model, we will now explain the interaction between the neurophysiological- and behavioral-outcomes.

Regarding brain and behavioral plasticity, researchers have argued that, if behavior changes, “there must be some change in organization or properties of the neural circuitry that produces the behavior” (Kolb, Gibb, & Robinson, 2003). Our model incorporates a bidirectional relation between neurophysiological- and behavioral-changes in an NFT session which is fundamental in operant conditioning. Our model indicates that these changes will occur simultaneously. However, they might not be proportionate over a given period of time. During an NFT session, structural and functional changes (due to plasticity) occur in the brain which are influenced by perceptions, predictions, a set-point determination, and adaptation to the set-point (demands). Simultaneously, in an NFT session, a behavior could be modified as a result of positive feedback (or reinforcement) and/or negative feedback (punishment). Studies have shown changes at micro levels (e.g., by looking at the parameters such as LTP and STDP) in the short-term, even within a single session. Significant changes at macro levels (or the functional level), however, may only occur after multiple training sessions. In this respect, Davelaar (2019) has argued “[a change in the functional level] operates on a timescale that covers multiple training sessions and is sensitive to consolidation processes that unfold during sleep. This stage involves updating striatal-thalamic and thalamo-cortical connections."

Commenting on the current debate, Thibault and Raz (2018) and (Micoulaud-Franchi & Fovet, 2018) suggested the effects of NFT should be interpreted through three distinct mechanisms: a) psychosocial, b) cognitive, and c) neurophysiological. Psychosocial refers to "the elements involved in the motivation for and expectation associated with participating in a clinical procedure, interacting with a practitioner, and interfacing with neurotechnology", and cognition refers to "the process of actively engaging in a form of mental or behavioral training, regardless of the type or contingency of the feedback provided."(Thibault & Raz, 2018).

With respect to our model, we argue that the immediate effects of NFT on the micro and behavioral levels can be observed, although functional changes will only be observed after multiple training sessions. However, researchers should bear in mind that the initial behavioral changes are not stable and would partially be due to psychosocial and cognitive factors.

In conclusion, in an NFT intervention, the functional changes that researchers expect to observe as the specific effects of a trained protocol require time to become established in the brain. This means that the initial changes in the neural circuitry which generate a behavior are not yet well-established. The behavioral outcomes in the initial stage thus encompass unspecific and/or less well-established neurophysiological changes, as well as psychosocial and cognitive factors. Tinga et al. (2019) have recently shown that, in general, neurophysiological outcomes have smaller effect sizes than those of behavioral outcomes. This discrepancy between neurophysiological and behavioral evidence has been reported in the field of NFT. Now, with respect to the prediction that our model makes about NFT mechanisms, the brain, as a regulator, develops patterns to meet demands placed on it. Therefore, we predict that a longer intervention not only leads to specific structural changes but also to the functional changes required to (develop patterns to) modify a particular behavior. Longer interventions then enable researchers to observe changes at the neurophysiological-level that are comparable to the behavioral.

Third conclusion; expectations about NFT process and outcomes

The third aim of the current paper was to discuss outstanding issues regarding expected outcomes of NFT and the reasons that might differentiate the consequences of NFT between the medical treatments (or clinical application) and optimize performance applications, and to provide ideas on how our framework may aid in solving these issues. From a theoretical perspective, we can conclude that, when NFT is applied to optimize performance, there is no reason to assume any changes in brain activity in a rest condition in the first place. Moreover, such changes would most likely even cause probable negative side effects. This may, for example, be observed in a situation in which, following NFT and in a resting condition, a healthy participant shows a consistently high level in the power/amplitude of a fast frequency band such as beta (15–30 Hz) as compared to their baseline. However, we have also explained that, when NFT is applied to optimize performance, there is one exception to this rule: Due to the neural efficiency induced by NFT, one can expect to observe prolonged changes in brain activity after NFT is applied to enhance alpha activity (7-13 Hz). Alpha activity is indicative of the inhibition and suppression of unnecessary or irrelevant information processing, especially during the resting state. We also argued that, after learning to modify their brain activity, a person should be able to up- and down-regulate the trained frequency more freely based on physiological demands. Furthermore, with respect to our model, we comment on current debate regarding the interaction between neurophysiological and behavioral changes that can be induced by NFT. We argued that the immediate (and non-stable) effects of NFT on behavior can be observed after a few sessions, even though functional changes might not be well established. However, longer interventions are required to stabilize behavioral changes and enable researchers to observe changes at the neurophysiological level which are comparable to the behavioral level. These theoretical concerns could provide insights for future research.

General conclusion

NFT continues to gain widespread interest and attention from researchers, both in clinical and performance-related disciplines. It has, therefore, become necessary to define the theoretical framework and the neural mechanisms associated with NFT and to differentiate between its probable outcomes. This paper has identified the importance of self-regulation and the role of operant conditioning for inducing physiological self-regulation and, consequently, optimizing a behavior or function of interest. In addition, the resemblance between control system elements, hemostasis, and allostasis and those of NFT were discussed and therefore developed a new theoretical model to explain the neural mechanisms underlying of NFT. This paper has also provided more insight into the neuro-psycho-physiological factors that influence learning and regulation: the strengthening of synapses, the concurrent occurrence of a strong pre- and post-synaptic activation of neurotransmitters, probable changes in white and gray matters of the brain, and the functional plasticity that can be attributed to NFT. The most important contribution of this paper has been to show that physiological regulation induced by NFT is based on the framework of allostasis, and that NFT may optimize adaptation to new demands in four stages, which we have named the allostasis four-stage model of NFT: A) by more accurately perceiving internal and external demands; B) by predicting the internal and external state of the body and its future output; C) by more appropriately determining new set-points (which is an efficient trade-off between new demands and the current internal state); and D) by more efficiently responding to new set-points (when the brain assumes the role of an effector). This perspective review also supports the idea that the greatest asset of NFT is that changes resulting from interventions occur under physiologically normal conditions, which are clearly required for clinical applications. However, this perspective review proposes that neurophysiological changes resulting from NFT interventions occurring under physiologically abnormal conditions may differ for non-clinical applications. Compared to other pharmacotherapy and non-invasive brain stimulation (such as rTMS and tDCS) NFT is purely an endogenous technique, whereby physiological-regulation is invoked by the mechanism of action itself, i.e., from the "inside out" rather than from the "outside in" (Ros et al., 2014). It is therefore assumed (as evident in the seminal study by Joe Kamiya) that the alteration induced by NFT is under volitional control when the process of learning is complete. More evidence on volitional control on brain oscillatory activity following the termination of NFT would help us to establish a greater degree of accuracy on this matter. In general, therefore, the theoretical implications of these findings offer promise for NFT as a means of influencing learning and self-regulation across a variety of normative and clinical groups.

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References

Andrasik, F., & Rime, C. (2007). chapter 121 - Biofeedback. In S. D. Waldman & J. I. Bloch (Eds.), *Pain Management* (pp. 1010-1020). Philadelphia: W.B. Saunders.

Arduin, P. J., Fregnac, Y., Shulz, D. E., & Ego-Stengel, V. (2013). "Master" neurons induced by operant conditioning in rat motor cortex during a brain-machine interface task. *J Neurosci, 33*(19), 8308-8320. doi:10.1523/jneurosci.2744-12.2013

Arns, M., de Ridder, S., Strehl, U., Breteler, M., & Coenen, A. (2009). Efficacy of neurofeedback treatment in ADHD: the effects on inattention, impulsivity and hyperactivity: a meta-analysis. *Clin EEG Neurosci, 40*(3), 180-189.

Awh, E., & Gehring, W. J. (1999). The anterior cingulate cortex lends a hand in response selection. *Nature Neuroscience, 2*, 853. doi:10.1038/13145

Banfield, J. F., Wyland, C. L., Macrae, C. N., Munte, T. F., & Heatherton, T. F. (2004). The cognitive neuroscience of self-regulation. *Handbook of self-regulation: Research, theory, and applications, 6283*.

Barkley, R. A. (2017). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psych.Bull., 121*, 65-94.

Baumeister, R. F., & Heatherton, T. F. (1996). Self-regulation failure: An overview. *Psychological inquiry, 7*(1), 1-15.

Beer, J. S. (2011). Neural Systems of Intrapersonal and Interpersonal Self-Esteem Maintenance. In J. Decety & J. T. Cacioppo (Eds.), *In The Oxford Handbook of Social Neuroscience* (pp. 599-613): Oxford University Press.

Bissiere, S., Humeau, Y., & Luthi, A. (2003). Dopamine gates LTP induction in lateral amygdala by suppressing feedforward inhibition. *Nat Neurosci, 6*(6), 587-592. doi:10.1038/nn1058

Bluschke, A., Broschwitz, F., Kohl, S., Roessner, V., & Beste, C. (2016). The neuronal mechanisms underlying improvement of impulsivity in ADHD by theta/beta

neurofeedback. *Scientific Reports, 6*, 31178. doi:10.1038/srep31178
Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature, 402*(6758), 179-181. doi:10.1038/46035
Bush, G., Valera, E. M., & Seidman, L. J. (2005). Functional neuroimaging of attention-deficit/hyperactivity disorder: A review and suggested future directions. *Biological Psychiatry, 57*(11), 1273-1284. doi:10.1016/j.biopsych.2005.01.034
Bush, G., Vogt, B. A., Holmes, J., Dale, A. M., Greve, D., Jenike, M. A., & Rosen, B. R. (2002). Dorsal anterior cingulate cortex: a role in reward-based decision making. *Proc Natl Acad Sci U S A, 99*(1), 523-528. doi:10.1073/pnas.012470999
Cannon, R. L., Lubar, J. F., Congedo, M., Thornton, K., Towler, K., & Hutchens, T. (2007). *The effects of neurofeedback training in the cognitive division of the anterior cingulate gyrus* (Vol. 117).
Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M. M., Noll, D., & Cohen, J. D. (1998). Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science, 280*(5364), 747-749.
Carter, C. S., Macdonald, A. M., Botvinick, M., Ross, L. L., Stenger, V. A., Noll, D., & Cohen, J. D. (2000). Parsing executive processes: strategic vs. evaluative functions of the anterior cingulate cortex. *Proceedings of the National Academy of Sciences, 97*(4), 1944-1948.
Cherkassky, V. L., Kana, R. K., Keller, T. A., & Just, M. A. (2006). Functional connectivity in a baseline resting-state network in autism. *Neuroreport, 17*(16), 1687-1690. doi:10.1097/01.wnr.0000239956.45448.4c
Clark, V. P., & Parasuraman, R. (2014). Neuroenhancement: enhancing brain and mind in health and in disease. *Neuroimage, 85 Pt 3*, 889-894. doi:10.1016/j.neuroimage.2013.08.071
Coben, R., Linden, M., & Myers, T. E. (2010). Neurofeedback for autistic spectrum disorder: a review of the literature. *Applied psychophysiology and biofeedback, 35*(1), 83-105.
Cohen, E. J., Quarta, E., Bravi, R., Granato, A., & Minciacchi, D. (2017). Neural plasticity and network remodeling: From concepts to pathology. *Neuroscience, 344*, 326-345. doi:https://doi.org/10.1016/j.neuroscience.2016.12.048
Cohen, R. A., Kaplan, R. F., Moser, D. J., Jenkins, M. A., & Wilkinson, H. (1999). Impairments of attention after cingulotomy. *Neurology, 53*(4), 819-824.
Colcombe, S. J., Erickson, K. I., Scalf, P. E., Kim, J. S., Prakash, R., McAuley, E., . . . Kramer, A. F. (2006). Aerobic exercise training increases brain volume in aging humans. *J Gerontol A Biol Sci Med Sci, 61*(11), 1166-1170.
Collura, T. F. (2014). *Technical Foundations of Neurofeedback*: Taylor & Francis.
Damasio, A. R., & Van Hoesen, G. W. (1983). Emotional disturbances associated with focal lesions of the limbic frontal lobe. *Neuropsychology of human emotion, 1*, 85-110.
Davelaar, E. J. (2018). Mechanisms of Neurofeedback: A Computation-theoretic Approach. *Neuroscience,*

378, 175-188. doi:10.1016/j.neuroscience.2017.05.052

Davelaar, E. J. (2019). *MULTI-STAGE THEORY OF NEUROFEEDBACK LEARNING*. Paper presented at the The Second Neuroadaptive Technology Conference.

De Ridder, D. T., & De Wit, J. B. (2006). Self-regulation in health behavior: Concepts, theories, and central issues. *Self-regulation in health behavior*, 1-23.

Dimitrov, M., Granetz, J., Peterson, M., Hollnagel, C., Alexander, G., & Grafman, J. (1999). Associative learning impairments in patients with frontal lobe damage. *Brain and cognition, 41*(2), 213-230.

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., & May, A. (2004). Neuroplasticity: changes in grey matter induced by training. *Nature, 427*(6972), 311-312. doi:10.1038/427311a

Draganski, B., Gaser, C., Kempermann, G., Kuhn, H. G., Winkler, J., Buchel, C., & May, A. (2006). Temporal and spatial dynamics of brain structure changes during extensive learning. *J Neurosci, 26*(23), 6314-6317. doi:10.1523/jneurosci.4628-05.2006

Duncan, J., & Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends Neurosci, 23*(10), 475-483.

Dworkin, B. R. (1986). Learning and long-term physiological regulation. In *Consciousness and Self-regulation* (pp. 163-182): Springer.

Elbert, T., Rockstroh, B., Lutzenberger, W., & Birbaumer, N. (2012). *Self-regulation of the brain and behavior*: Springer Science & Business Media.

Elliott, R., & Dolan, R. J. (1998). Neural response during preference and memory judgments for subliminally presented stimuli: a functional neuroimaging study. *J Neurosci, 18*(12), 4697-4704.

Emmert, K., Kopel, R., Sulzer, J., Bruhl, A. B., Berman, B. D., Linden, D. E. J., . . . Haller, S. (2016). Meta-analysis of real-time fMRI neurofeedback studies using individual participant data: How is brain regulation mediated? *Neuroimage, 124*(Pt A), 806-812. doi:10.1016/j.neuroimage.2015.09.042

Feldman, D. E. (2012). The spike timing dependence of plasticity. *Neuron, 75*(4), 556-571. doi:10.1016/j.neuron.2012.08.001

Fetz, E. E. (1969). Operant conditioning of cortical unit activity. *Science, 163*(3870), 955-958.

Fishbach, A., & Shah, J. Y. (2006). Self-control in action: implicit dispositions toward goals and away from temptations. *J Pers Soc Psychol, 90*(5), 820-832. doi:10.1037/0022-3514.90.5.820

Gallistel, C. R., & Matzel, L. D. (2013). The neuroscience of learning: beyond the Hebbian synapse. *Annu Rev Psychol, 64*, 169-200. doi:10.1146/annurev-psych-113011-143807

Gaume, A., Vialatte, A., Mora-Sánchez, A., Ramdani, C., & Vialatte, F. B. A psychoengineering paradigm for the neurocognitive mechanisms of biofeedback and neurofeedback. *Neuroscience & Biobehavioral Reviews*. doi:http://dx.doi.org/10.1016/j.neubiorev.2016.06.012

Gehring, W. J., & Fencsik, D. E. (2001). Functions of the medial frontal cortex in the processing of conflict and errors. *J Neurosci, 21*(23), 9430-9437.

Gehring, W. J., & Knight, R. T. (2000a). Prefrontal-cingulate interactions in action monitoring. *Nat Neurosci, 3*(5), 516-520. doi:10.1038/74899

Gehring, W. J., & Knight, R. T. (2000b). Prefrontal–cingulate interactions in action monitoring. *Nature neuroscience, 3*(5), 516-520.

Gerdes, L., Gerdes, P., Lee, S. W., & H Tegeler, C. (2013). HIRREM™: a noninvasive, allostatic methodology for relaxation and auto-calibration of neural oscillations. *Brain and Behavior, 3*(2), 193-205. doi:10.1002/brb3.116

Gerstner, W. (2011). Hebbian learning and plasticity. *From neuron to cognition via computational neuroscience*, 0-25.

Ghaziri, J., Tucholka, A., Larue, V., Blanchette-Sylvestre, M., Reyburn, G., Gilbert, G., . . . Beauregard, M. (2013). Neurofeedback training induces changes in white and gray matter. *Clin EEG Neurosci, 44*(4), 265-272. doi:10.1177/1550059413476031

Gollwitzer, P. M., & Brandstätter, V. (1997). Implementation intentions and effective goal pursuit. *Journal of personality and social psychology, 73*(1), 186.

Gopal, M. (2002). *Control Systems: Principles and Design*: McGraw-Hill Education (India) Pvt Limited.

Gruzelier, J. H. (2014a). EEG-neurofeedback for optimising performance. I : a review of cognitive and affective outcome in healthy participants. *Neuroscience & Biobehavioral Reviews, 44*, 124-141.

Gruzelier, J. H. (2014b). EEG-neurofeedback for optimising performance. II: creativity, the performing arts and ecological validity. *Neuroscience & Biobehavioral Reviews, 44*, 142-158.

Gruzelier, J. H. (2014c). EEG-neurofeedback for optimising performance. III: A review of methodological and theoretical considerations. *Neuroscience & Biobehavioral Reviews, 44*, 159-182.

Gruzelier, J. H., & Egner, T. (2004). Physiological self-regulation: Biofeedback and neurofeedback. In A. Williamon (Ed.), *Musical Excellence: Strategies and Techniques to Enhance Performance.* (pp. 197-219). London: Oxford University Press.

Gruzelier, J. H., & Egner, T. (2005). Critical validation studies of neurofeedback. *Child and Adolescent Psychiatric Clinics, 14*(1), 83-104.

Hare, T. A., Camerer, C. F., & Rangel, A. (2009). Self-control in decision-making involves modulation of the vmPFC valuation system. *Science, 324*(5927), 646-648. doi:10.1126/science.1168450

Hebb, D. O. (1949). *The organization of behavior* (D. O. Hebb Ed. Vol. 65): Wiley New York.

Hensel, H. (1981). Thermoreception and temperature regulation. *Monogr Physiol Soc, 38*, 1-321.

Hernandez, M., Denburg, N. L., & Tranel, D. (2009). Chapter 13 - A neuropsychological perspective on the role of the prefrontal cortex in reward processing and decision-making. In *Handbook of Reward and Decision Making* (pp. 291-306). New York: Academic Press.

Hinterberger, T., Veit, R., Strehl, U., Trevorrow, T., Erb, M., Kotchoubey, B., . . . Birbaumer, N. (2003). Brain areas activated in fMRI during self-regulation of slow cortical potentials (SCPs). *Exp Brain Res, 152*(1), 113-122. doi:10.1007/s00221-003-1515-4

Hofmann, W., Schmeichel, B. J., & Baddeley, A. D. (2012). Executive functions and self-regulation.

Trends Cogn Sci, 16(3), 174-180. doi:10.1016/j.tics.2012.01.006

Hohenfeld, C., Nellessen, N., Dogan, I., Kuhn, H., Muller, C., Papa, F., . . . Reetz, K. (2017). Cognitive Improvement and Brain Changes after Real-Time Functional MRI Neurofeedback Training in Healthy Elderly and Prodromal Alzheimer's Disease. *Front Neurol, 8*, 384. doi:10.3389/fneur.2017.00384

Hölzel, B. K., Carmody, J., Vangel, M., Congleton, C., Yerramsetti, S. M., Gard, T., & Lazar, S. W. (2011). Mindfulness practice leads to increases in regional brain gray matter density. *Psychiatry research, 191*(1), 36-43. doi:10.1016/j.pscychresns.2010.08.006

Hurley, K. M., Herbert, H., Moga, M. M., & Saper, C. B. (1991). Efferent projections of the infralimbic cortex of the rat. *J Comp Neurol, 308*(2), 249-276. doi:10.1002/cne.903080210

Ilg, R., Wohlschlager, A. M., Gaser, C., Liebau, Y., Dauner, R., Woller, A., . . . Muhlau, M. (2008). Gray matter increase induced by practice correlates with task-specific activation: a combined functional and morphometric magnetic resonance imaging study. *J Neurosci, 28*(16), 4210-4215. doi:10.1523/jneurosci.5722-07.2008

Kaas, J. H. (2001). Neural Plasticity A2 - Smelser, Neil J. In P. B. Baltes (Ed.), *International Encyclopedia of the Social & Behavioral Sciences* (pp. 10542-10546). Oxford: Pergamon.

Kamiya, J. (1962). *Conditioned discrimination of the EEG alpha rhythm in humans*. Paper presented at the the Western Psychological, San Francisco, California.

Kane, M. J., Bleckley, M. K., Conway, A. R., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *J Exp Psychol Gen, 130*(2), 169-183.

Kanosue, K., Crawshaw, L. I., Nagashima, K., & Yoda, T. (2010). Concepts to utilize in describing thermoregulation and neurophysiological evidence for how the system works. *European journal of applied physiology, 109*(1), 5-11.

Kiehl, K. A., Liddle, P. F., & Hopfinger, J. B. (2000). Error processing and the rostral anterior cingulate: an event-related fMRI study. *Psychophysiology, 37*(2), 216-223.

Knutson, B., Westdorp, A., Kaiser, E., & Hommer, D. (2000). FMRI visualization of brain activity during a monetary incentive delay task. *Neuroimage, 12*(1), 20-27. doi:10.1006/nimg.2000.0593

Kober, S. E., Witte, M., Stangl, M., Väljamäe, A., Neuper, C., & Wood, G. (2015). Shutting down sensorimotor interference unblocks the networks for stimulus processing: An SMR neurofeedback training study. *Clinical Neurophysiology, 126*(1), 82-95. doi:10.1016/j.clinph.2014.03.031

Kolb, B., Gibb, R., & Robinson, T. E. (2003). Brain Plasticity and Behavior. *Current Directions in Psychological Science, 12*(1), 1-5. doi:10.1111/1467-8721.01210

Kringelbach, M. L., & Berridge, K. C. (2016). Neuroscience of reward, motivation, and drive. In *Recent Developments in Neuroscience Research on Human Motivation* (pp. 23-35): Emerald Group Publishing Limited.

Kulichenko, A. M., Fokina, Y. O., & Pavlenko, V. B. (2009). Changes in EEG Rhythms and Spike Activity of Brainstem Dopaminergic Neurons Induced by Neurofeedback Sessions in Cats.

Neurophysiology, 41(3), 196. doi:10.1007/s11062-009-9093-0

Landers, D. M., Petruzzello, S. J., Salazar, W., Crews, D. J., Kubitz, K. A., Gannon, T. L., & Han, M. (1991). The influence of electrocortical biofeedback on performance in pre-elite archers. *Med Sci Sports Exerc, 23*(1), 123-129. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1997806

LeBlanc, S. E., & Coughanowr, D. R. (2008). *Process Systems Analysis and Control*: McGraw-Hill Higher Education.

Levine, B., Stuss, D. T., Milberg, W. P., Alexander, M. P., Schwartz, M., & MacDonald, R. (1998). The effects of focal and diffuse brain damage on strategy application: Evidence from focal lesions, traumatic brain injury and normal aging. *Journal of the International Neuropsychological Society, 4*(3), 247-264.

Liddle, P. F., Kiehl, K. A., & Smith, A. M. (2001). Event-related fMRI study of response inhibition. *Hum Brain Mapp, 12*(2), 100-109.

Luk, C. H., & Wallis, J. D. (2013). Choice coding in frontal cortex during stimulus-guided or action-guided decision-making. *J Neurosci, 33*(5), 1864-1871. doi:10.1523/jneurosci.4920-12.2013

Luria, A. (1966). *Higher cortical functions in man*: New York: Basic Books.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288*(5472), 1835-1838.

Malloy, P., Bihrle, A., Duffy, J., & Cimino, C. (1993). The orbitomedial frontal syndrome. *Archives of Clinical Neuropsychology, 8*(3), 185-201. doi:10.1093/arclin/8.3.185

Markram, H., Gerstner, W., & Sjöström, P. J. (2011). A History of Spike-Timing-Dependent Plasticity. *Frontiers in Synaptic Neuroscience, 3*, 4. doi:10.3389/fnsyn.2011.00004

McEntee, W. J., & Crook, T. H. (1993). Glutamate: its role in learning, memory, and the aging brain. *Psychopharmacology (Berl), 111*(4), 391-401.

McEwen, B. S. (2016). Chapter 5 - Central Role of the Brain in Stress and Adaptation: Allostasis, Biological Embedding, and Cumulative Change. In G. Fink (Ed.), *Stress: Concepts, Cognition, Emotion, and Behavior* (pp. 39-55). San Diego: Academic Press.

McEwen, B. S., & Wingfield, J. C. (2003). The concept of allostasis in biology and biomedicine. *Horm Behav, 43*(1), 2-15. doi:https://doi.org/10.1016/S0018-506X(02)00024-7

Menon, V., Adleman, N. E., White, C. D., Glover, G. H., & Reiss, A. L. (2001). Error-related brain activation during a Go/NoGo response inhibition task. *Hum Brain Mapp, 12*(3), 131-143.

Micoulaud-Franchi, J. A., & Fovet, T. (2018). A framework for disentangling the hyperbolic truth of neurofeedback: Comment on Thibault and Raz (2017). *Am Psychol, 73*(7), 933-935. doi:10.1037/amp0000340

Miller, E. K. (2000). The prefrontal cortex and cognitive control. *Nat Rev Neurosci, 1*(1), 59-65. doi:10.1038/35036228

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual review of neuroscience, 24*(1), 167-202. doi:10.1146/annurev.neuro.24.1.167

Miller, J. D., Sanghera, M. K., & German, D. C. (1981). Mesencephalic dopaminergic unit activity in the behaviorally conditioned rat. *Life Sciences, 29*(12), 1255-1263. doi:https://doi.org/10.1016/0024-3205(81)90231-9

Miller, N. E. (1978). Biofeedback and Visceral Learning. *Annual review of psychology, 29*(1), 373-404. doi:10.1146/annurev.ps.29.020178.002105

Miller, R. (1981). Meaning and purpose in the intact brain a philosophical, psychological, and biological account of conscious processes. In. Oxford :: Clarendon Press.

Mirenowicz, J., & Schultz, W. (1994). Importance of unpredictability for reward responses in primate dopamine neurons. *J Neurophysiol, 72*(2), 1024-1027.

Mirifar, A., Keil, A., Beckmann, J., & Ehrlenspiel, F. (2019). No Effects of Neurofeedback of Beta Band Components on Reaction Time Performance. *Journal of Cognitive Enhancement, 3*(3), 251-260.

Monastra, V. J. (2008). Quantitative electroencephalography and attention-deficit/hyperactivity disorder: implications for clinical practice. *Curr Psychiatry Rep, 10*(5), 432-438. doi:10.1007/s11920-008-0069-3

Moore, N. C. (2000). A review of EEG biofeedback treatment of anxiety disorders. *Clinical EEG and Neuroscience, 31*(1), 1-6.

Mulholland, T. B. (1984). Concepts of Control in Biofeedback. In T. Elbert, B. Rockstroh, W. Lutzenberger, & N. Birbaumer (Eds.), *Self-Regulation of the Brain and Behavior* (pp. 277-295). Berlin, Heidelberg: Springer Berlin Heidelberg.

Munivenkatappa, A., Rajeswaran, J., Indira Devi, B., Bennet, N., & Upadhyay, N. (2014). EEG Neurofeedback therapy: Can it attenuate brain changes in TBI? *NeuroRehabilitation, 35*(3), 481-484.

Ninaus, M., Kober, S. E., Witte, M., Koschutnig, K., Stangl, M., Neuper, C., & Wood, G. (2013). Neural substrates of cognitive control under the belief of getting neurofeedback training. *Frontiers in human neuroscience, 7*, 914. doi:10.3389/fnhum.2013.00914

Nishino, H., Ono, T., Muramoto, K., Fukuda, M., & Sasaki, K. (1987). Neuronal activity in the ventral tegmental area (VTA) during motivated bar press feeding in the monkey. *Brain Res, 413*(2), 302-313.

Niv, S. (2013). Clinical efficacy and potential mechanisms of neurofeedback. *Personality and Individual Differences, 54*(6), 676-686.

Oblak, E. F., Lewis-Peacock, J. A., & Sulzer, J. S. (2017). Self-regulation strategy, feedback timing and hemodynamic properties modulate learning in a simulated fMRI neurofeedback environment. *PLoS Comput Biol, 13*(7), e1005681. doi:10.1371/journal.pcbi.1005681

Ossadtchi, A., Shamaeva, T., Okorokova, E., Moiseeva, V., & Lebedev, M. A. (2017). Neurofeedback learning modifies the incidence rate of alpha spindles, but not their duration and amplitude. *Sci Rep, 7*(1), 3772. doi:10.1038/s41598-017-04012-0

Pandria, N., Kovatsi, L., Vivas, A. B., & Bamidis, P. D. (2018). Resting-state Abnormalities in Heroin-dependent Individuals. *Neuroscience, 378*, 113-145. doi:10.1016/j.neuroscience.2016.11.018

Pandya, D. N., & Barnes, C. L. (1987). Architecture and connections of the frontal lobe. In *The frontal lobes* *revisited.* (pp. 41-72). New York, NY, US: The IRBN Press.

Papoutsi, M., Weiskopf, N., Langbehn, D., Reilmann, R., Rees, G., & Tabrizi, S. J. (2018). Stimulating neural plasticity with real-time fMRI neurofeedback in Huntington's disease: A proof of concept study. *39*(3), 1339-1353. doi:10.1002/hbm.23921

Paret, C., Zahringer, J., Ruf, M., Gerchen, M. F., Mall, S., Hendler, T., . . . Ende, G. (2018). Monitoring and control of amygdala neurofeedback involves distributed information processing in the human brain. *Hum Brain Mapp*. doi:10.1002/hbm.24057

Paulus, M. P., Hozack, N., Frank, L., & Brown, G. G. (2002). Error rate and outcome predictability affect neural activation in prefrontal cortex and anterior cingulate during decision-making. *Neuroimage, 15*(4), 836-846. doi:10.1006/nimg.2001.1031

Paus, T. (2001). Primate anterior cingulate cortex: where motor control, drive and cognition interface. *Nat Rev Neurosci, 2*(6), 417-424. doi:10.1038/35077500

Pawlak, V., Wickens, J. R., Kirkwood, A., & Kerr, J. N. D. (2010). Timing is not Everything: Neuromodulation Opens the STDP Gate. *Frontiers in Synaptic Neuroscience, 2*, 146. doi:10.3389/fnsyn.2010.00146

Posner, M. I., & Rothbart, M. K. (1998). Attention, self-regulation and consciousness. *Philos Trans R Soc Lond B Biol Sci, 353*(1377), 1915-1927. doi:10.1098/rstb.1998.0344

Purves, D., Fitzpatrick, D., Katz, L. C., Lamantia, A. S., McNamara, J. O., Williams, S. M., & Augustine, G. J. (2001). *Neuroscience*: Sinauer Associates.

Raichle, M. E., Fiez, J. A., Videen, T. O., MacLeod, A. M., Pardo, J. V., Fox, P. T., & Petersen, S. E. (1994). Practice-related changes in human brain functional anatomy during nonmotor learning. *Cereb Cortex, 4*(1), 8-26.

Raine, A., & Yang, Y. (2006). Neural foundations to moral reasoning and antisocial behavior. *Social cognitive and affective neuroscience, 1*(3), 203-213. doi:10.1093/scan/nsl033

Ramsay, D. S., & Woods, S. C. (2014). Clarifying the Roles of Homeostasis and Allostasis in Physiological Regulation. *Psychological review, 121*(2), 225-247. doi:10.1037/a0035942

Reiner, M., Gruzelier, J. H., Bamidis, P. D., & Auer, T. (2018). The Science of Neurofeedback: Learnability and Effects. *Neuroscience, 378*, 1-10. doi:https://doi.org/10.1016/j.neuroscience.2018.04.024

Ring, C., Cooke, A., Kavussanu, M., McIntyre, D., & Masters, R. (2015). Investigating the efficacy of neurofeedback training for expediting expertise and excellence in sport. *Psychology of Sport and Exercise, 16*, 118-127.

Rolls, E. (2000). *The Orbitofrontal Cortex and Reward* (Vol. 10).

Romo, R., & Schultz, W. (1990). Dopamine neurons of the monkey midbrain: contingencies of responses to active touch during self-initiated arm movements. *J Neurophysiol, 63*(3), 592-606.

Ros, T., Baars, B. J., Lanius, R. A., & Vuilleumier, P. (2014). Tuning pathological brain oscillations with neurofeedback: A systems neuroscience framework. *Frontiers in human neuroscience, 8*(DEC), 1008. doi:10.3389/fnhum.2014.01008

Russell-Chapin, L., Kemmerly, T., Liu, W. C., Zagardo, M. T., Chapin, T., Dailey, D., & Dinh, D. (2013). The Effects of Neurofeedback in the Default Mode Network: Pilot

Study Results of Medicated Children with ADHD. *Journal of Neurotherapy, 17*(1), 35-42. doi:10.1080/10874208.2013.759017

Sanei, S., & Chambers, J. A. (2007). *EEG signal processing*: John Wiley & Sons.

Schabus, M. (2017). Reply: On assessing neurofeedback effects: should double-blind replace neurophysiological mechanisms? *Brain, 140*(10), e64-e64. doi:10.1093/brain/awx212

Schabus, M. (2018). Reply: Noisy but not placebo: defining metrics for effects of neurofeedback. *Brain, 141*(5), e41-e41. doi:10.1093/brain/awy061

Schultz, W. (2002). Getting formal with dopamine and reward. *Neuron, 36*(2), 241-263.

Shinners, S. M. (1998). *Modern control system theory and design*: John Wiley & Sons.

Shirvalkar, P. R. (2009). Hippocampal neural assemblies and conscious remembering. *J Neurophysiol, 101*(5), 2197-2200. doi:10.1152/jn.91363.2008

Siddiqui, S. V., Chatterjee, U., Kumar, D., Siddiqui, A., & Goyal, N. (2008). Neuropsychology of prefrontal cortex. *Indian Journal of Psychiatry, 50*(3), 202-208. doi:10.4103/0019-5545.43634

Sitaram, R., Ros, T., Stoeckel, L., Haller, S., Scharnowski, F., Lewis-Peacock, J., . . . Sulzer, J. (2017). Closed-loop brain training: the science of neurofeedback. *Nat Rev Neurosci, 18*(2), 86-100. doi:10.1038/nrn.2016.164

Sohlberg, M. M., & Mateer, C. A. (1989). *Introduction to cognitive rehabilitation: Theory and practice*: Guilford Press.

Somjen, G. G. (1992). The missing error signal—regulation beyond negative feedback. *Physiology, 7*(4), 184-185.

Sorger, B., Kamp, T., Weiskopf, N., Peters, J. C., & Goebel, R. (2018). When the Brain Takes 'BOLD' Steps: Real-Time fMRI Neurofeedback Can Further Enhance the Ability to Gradually Self-regulate Regional Brain Activation. *Neuroscience, 378*, 71-88. doi:10.1016/j.neuroscience.2016.09.026

Spence, S. A., & Frith, C. D. (1999). Towards a functional anatomy of volition. *Journal of consciousness studies, 6*(8-9), 11-29.

Stephan, K. E., Manjaly, Z. M., Mathys, C. D., Weber, L. A., Paliwal, S., Gard, T., . . . Petzschner, F. H. (2016). Allostatic Self-efficacy: A Metacognitive Theory of Dyshomeostasis-Induced Fatigue and Depression. *Front Hum Neurosci, 10*, 550. doi:10.3389/fnhum.2016.00550

Sterling, P. (2012). Allostasis: a model of predictive regulation. *Physiology & Behavior, 106*(1), 5-15.

Sterling, P. (2018). Predictive regulation and human design. *eLife, 7*, e36133. doi:10.7554/eLife.36133

Sterling, P., & Eyer, J. (1988). Allostasis: A new paradigm to explain arousal pathology. In *Handbook of life stress, cognition and health.* (pp. 629-649). Oxford, England: John Wiley & Sons.

Sterling, P., & Laughlin, S. (2015). *Principles of Neural Design*: MIT Press.

Stuss, D. T. (1991). Self, Awareness, and the Frontal Lobes: A Neuropsychological Perspective. In J. Strauss & G. R. Goethals (Eds.), *The Self: Interdisciplinary Approaches* (pp. 255-278). New York, NY: Springer New York.

Stuss, D. T., & Levine, B. (2002). Adult clinical neuropsychology: lessons from studies of the frontal lobes. *Annual review of psychology, 53*(1), 401-433.

Sulzer, J., Sitaram, R., Blefari, M. L., Kollias, S., Birbaumer, N., Stephan, K. E., . . . Gassert, R. (2013). Neurofeedback-mediated self-regulation of the dopaminergic midbrain. *Neuroimage, 83*, 817-825. doi:10.1016/j.neuroimage.2013.05.115

Takahashi, Y. K., Roesch, M. R., Wilson, R. C., Toreson, K., O'Donnell, P., Niv, Y., & Schoenbaum, G. (2011). Expectancy-related changes in firing of dopamine neurons depend on orbitofrontal cortex. *Nat Neurosci, 14*(12), 1590-1597. doi:10.1038/nn.2957

Tang, Y., Lu, Q., Fan, M., Yang, Y., & Posner, M. I. (2012). Mechanisms of white matter changes induced by meditation. *Proceedings of the National Academy of Sciences of the United States of America, 109*(26), 10570-10574. doi:10.1073/pnas.1207817109

Ter Horst, G. J., Hautvast, R. W., De Jongste, M. J., & Korf, J. (1996). Neuroanatomy of cardiac activity-regulating circuitry: a transneuronal retrograde viral labelling study in the rat. *Eur J Neurosci, 8*(10), 2029-2041. doi:10.1111/j.1460-9568.1996.tb00723.x

Terreberry, R. R., & Neafsey, E. J. (1987). The rat medial frontal cortex projects directly to autonomic regions of the brainstem. *Brain Research Bulletin, 19*(6), 639-649. doi:https://doi.org/10.1016/0361-9230(87)90050-5

Thibault, R. T., Lifshitz, M., & Raz, A. (2016). The self-regulating brain and neurofeedback: Experimental science and clinical promise. *Cortex, 74*, 247-261. doi:10.1016/j.cortex.2015.10.024

Thibault, R. T., & Raz, A. (2017). The psychology of neurofeedback: Clinical intervention even if applied placebo. *Am Psychol, 72*(7), 679-688. doi:10.1037/amp0000118

Thibault, R. T., & Raz, A. (2018). A consensus framework for neurofeedback research (and the perils of unfounded neuroreductionism): Reply to Micoulaud-Franchi and Fovet (2018). *Am Psychol, 73*(7), 936-937. doi:10.1037/amp0000366

Thompson, L. (2004). Electroencephalographic Applications.

Tinga, A. M., de Back, T. T., & Louwerse, M. M. (2019). Non-invasive neurophysiological measures of learning: A meta-analysis. *Neurosci Biobehav Rev, 99*, 59-89. doi:10.1016/j.neubiorev.2019.02.001

Turrigiano, G. (2012). Homeostatic Synaptic Plasticity: Local and Global Mechanisms for Stabilizing Neuronal Function. *Cold Spring Harbor Perspectives in Biology, 4*(1), a005736. doi:10.1101/cshperspect.a005736

van Boxtel, G. J., & Gruzelier, J. H. (2014). Neurofeedback: introduction to the special issue. *Biol Psychol, 95*, 1-3. doi:10.1016/j.biopsycho.2013.11.011

van Kesteren, M. T. R., Fernández, G., Norris, D. G., & Hermans, E. J. (2010). Persistent schema-dependent hippocampal-neocortical connectivity during memory encoding and postencoding rest in humans. *Proceedings of the National Academy of Sciences of the United States of America, 107*(16), 7550-7555. doi:10.1073/pnas.0914892107

Verberne, A. J. M., & Owens, N. C. (1998). Cortical Modulation of theCardiovascular System. *Progress in Neurobiology, 54*(2), 149-168. doi:https://doi.org/10.1016/S0301-0082(97)00056-7

Vogt, B. A., Vogt, L., Farber, N. B., & Bush, G. (2005). Architecture and neurocytology of monkey cingulate gyrus. *Journal of Comparative Neurology, 485*(3), 218-239. doi:10.1002/cne.20512

Wickens, J. (1990). Striatal dopamine in motor activation and reward-mediated learning: steps towards a unifying model. *J Neural Transm Gen Sect, 80*(1), 9-31.

Wiener, N. (2019). *Cybernetics or Control and Communication in the Animal and the Machine*: MIT press.

Witte, M., Kober, S. E., & Wood, G. (2018). Noisy but not placebo: defining metrics for effects of neurofeedback. *Brain.*

Wyland, C. L., Kelley, W. M., Macrae, C. N., Gordon, H. L., & Heatherton, T. F. (2003). Neural correlates of thought suppression. *Neuropsychologia, 41*(14), 1863-1867.

Wyrwicka, W., & Sterman, M. B. (1968). Instrumental conditioning of sensorimotor cortex EEG spindles in the waking cat. *Physiology & behavior, 3*(5), 703-707.

Zoefel, B., Huster, R. J., & Herrmann, C. S. (2011). Neurofeedback training of the upper alpha frequency band in EEG improves cognitive performance. *Neuroimage, 54*(2), 1427-1431. doi:10.1016/j.neuroimage.2010.08.078

Zotev, V., Krueger, F., Phillips, R., Alvarez, R. P., Simmons, W. K., Bellgowan, P., . . . Bodurka, J. (2011). Self-regulation of amygdala activation using real-time FMRI neurofeedback. *PLOS ONE, 6*(9), e24522. doi:10.1371/journal.pone.0024522

Zsoldos, E., & Ebmeier, K. P. (2016). Chapter 38 - Aging and Psychological Stress. In G. Fink (Ed.), *Stress: Concepts, Cognition, Emotion, and Behavior* (pp. 311-323). San Diego: Academic Press.

General discussion

The interest in NFT is steadily increasing and is receiving more and more attention from researchers in different disciplines including clinical and performance related applications. It is, therefore, necessary to identify the neural mechanisms associated with NFT, and to differentiate between its applications in these disciplines. This project was undertaken first to determine NFT's effectiveness at improving athletes' performance and then to investigate the effects of different components of the EEG Beta band frequency on the attention and response times of athletes. Moreover, while the first two articles of this dissertation mainly examined the effect of NFT on athletes' performance and developed criteria enabling researchers to evaluate the quality of their findings, the third article focused on the psychophysiological framework and neural mechanisms underlying NFT.

To address the first question I presented an overview of empirical studies examining NFT's effects on athletes' performance, and then evaluated the studies in light of NFT-specific and general methodological criteria. The results indicate that, thus far, the majority of published studies supports the effectiveness of NFT at improving athletes' performance of a specific sports task and/or in relevant mediators such as cognition and affect. On closer inspection, however, evidence for specific protocols' effectiveness in enhancing sports performance became rather weak. The second question was examined by reducing the power ratio between Theta (4-7 Hz) and mid Beta (15-18 Hz) and enhancing power in the low Beta range (or sensory motor rhythm [SMR], 12-15 Hz) in a group of soccer players. My hypotheses regarding the regulation of trained brain oscillatory activity during task execution and behavioral outcomes were not supported. The questions were whether TBR training selectively improves SRT performance and whether SMR training selectively enhances CRT performance. This study was unable to replicate findings in previous studies showing the effectiveness of the above mentioned NFT training protocols on RT performance. However, there were small differences in my study design: I investigated the effectiveness of the training protocols on a different category of participants, used different types of RTs tests, and slightly modified the experimental design by monitoring the effects of interventions before, during, and after training sessions, as well as during task execution. From a more general perspective, my results also fuels the continuing debate about the effectiveness of NFT for optimizing athletic performance and the effectiveness of NFT as a whole. The results of my study, with a control/placebo group, do not help researchers answer the questions around NFT and suggest that evidence is weak for promoting frequency-specific NFT to improve the attention and RT in athletes in contrast to other studies with different groups. The findings reported here, demonstrate the difficulty of transferring successful protocols from clinical or non-athletic applications to a more specific population like athletes.

On the question of the psychophysiological framework and neural mechanisms underlying NFT, this dissertation proposes that physiological regulation induced by NFT is based on the framework of allostasis ("allostasis four-stage model of NFT"), and that NFT may optimize adaptation to new demands in four stages. The greatest asset of the allostasis four-stage model is that researchers and practitioners can distinguish between different applications and their respective outcome expectations: For clinical applications, more permanent changes in the trained frequency, resulting from interventions, should occur under the resting condition. However, in non-clinical applications, the model indicates that changes resulting from NFT should not occur under the resting condition, because these changes in the trained frequency should be limited to training time and task execution. The only exception to this theory is sustained changes in the resting state, in non-clinical applications, when an increase in the level of amplitude/power of alpha frequency (7-13 Hz) is observed. After an NFT intervention, the brain suppresses the processing of irrelevant information and more efficiently detects and processes relevant information of internal and external stimuli.

The description of the allostasis four-stage model of NFT regarding the interaction between neurophysiological- and behavioral outcomes also accords with my earlier argument (in the systematic review) that the training schedule (consisting of the number of sessions, the duration of each session, the inter-session interval) plays a crucial role when considering the longevity and stability of effectiveness. My model postulates a bidirectional, concurrent relation between neurophysiological- and behavioral-changes during an NFT session, and in operant conditioning this relation is axiomatic. The desired changes, however, might not remain equivalent over a given period of time. During a session, structural and functional changes (due to plasticity) occur in the brain which are influenced by perceptions, predictions, a set-point determination, and adaptation to the set-point (demands). Simultaneously, in an NFT session, a behavior can be modified as a result of positive feedback and/or negative. Studies have shown changes at micro levels in the short-term, even within a single session. Significant macro level changes (or the functional level), however, may only occur after multiple training sessions. With respect to my model, I argue that the immediate effects of NFT on the micro and behavioral levels can be observed, although only after multiple training sessions will functional changes be observed. However, researchers should bear in mind that the initial behavioral changes are not stable and are partially due to psychosocial and cognitive factors. In conclusion, in an NFT intervention, the functional changes that researchers expect to observe as the specific effects of a trained protocol require time to become established in the brain. Accordingly, the initial changes in the neural circuitry which generate a behavior have not yet been engrained. The behavioral outcomes in the initial stage thus encompass unspecific and/or not-well-established neurophysiological changes, as well as psychosocial and cognitive factors. Referring back to the empirical elements of this project, a further study could add a control group of non-athletes to not only investigate the effectiveness of NFT and differentiate the potential effects between training protocols but also more precisely verify such effects among groups (e.g. patients vs. non-patients and/or athletes). Another option would be to extend the intervention sessions beyond 10 sessions as a longer intervention leads to significant effects, and if effects are found evaluate its duration, as a long term effects of the intervention. From a practical perspective, it has been argued that neurocognitive effects of sleep have direct implications for self- regulatory processes, that sleep is a strong predictor of numerous self-regulatory outcomes, and that it can illuminate important contemporary debates about capacity for intentional self- regulatory behavior (Krizan & Hisler, 2016). Thus, a future study could add a short nap before and/or after NFT or schedule the training sessions in the morning, with a short interval, when the participants wake up or in the late evening before participants go to bed to investigate the interaction and possible effects of sleep on NFT's outcome. Notwithstanding its promise, NFT faces several challenges, including the failure of some individuals to achieve self-regulation, even after repeated training. Indeed, a substantial proportion — up to 30% — of participants in neurofeedback studies fail to self-regulate specific brain activity (Sitaram et al., 2017; Weber, Köberl, Frank, & Doppelmayr, 2011). By considering the time and energy that need to be spent on training, it is useful and worthwhile to predict whether a participant will learn to regulate the EEG rhythms in advance. Recent evidence suggests that the most likely causes of inter-individual differences in learning capacity for regulating EEG rhythms is structural integrity and the myelination quality of deep white matter structures, such as the corpus callosum, cingulum, and superior fronto-occipital fascicle (Halder et al., 2013). Thus, future studies should consider this issue for homogeneity as well as saving time and energy.

If the debates in the field are to be moved forward, a better understanding of changes in the trained frequency bands in different conditions (within- and between-sessions and during task execution) needs to be provided and discussed. Considerably more work will need to be done on replicating and extending NFT’s effect size with larger sample sizes. Providing more information about the rationale for a selected training protocol and the association with the desired outcome(s) could also help to better understand a protocol-specific effects.

Conclusion

Taken together, in general, the theoretical implications of this dissertation suggest neurophysiological regulation induced by NFT is based on the framework of allostasis, and that NFT may optimize adaptation to new demands in four stages, which was named the allostasis four-stage model of NFT. With respect to optimizing the performance-related application of NFT, however, much remains to be investigated, including frequencies specific effects on a particular sport disciplines also on different aspects of athletic performance e.g., mediators such as cognition and affect/emotion that can influence performance, transferring the learned self-regulation skills to the field (where no feedback is provided), the necessity of changes which have been observed in unexpected conditions, such as resting.

This dissertation: by considering the guidelines derived from the systematic review, the outcomes of the empirical study, and the proposed model "allostasis four-stage model of NFT" that describe the stages engaged in the process of self-regulation and related neurophysiological modification induced by NFT, has thrown up many questions in need of further investigation.

References

Alhiyali, M. I., Ishak, A. J. B., Ahmad, S. A. B., Ramli, H. R. H., & Sulaiman, W. A. W. (2018). A Review in Modification Food-Intake Behavior by Brain Stimulation: Excess Weight Cases. *NeuroQuantology, 16*(12).

Arain, M., Campbell, M. J., Cooper, C. L., & Lancaster, G. A. (2010). What is a pilot or feasibility study? A review of current practice and editorial policy. *BMC Med Res Methodol, 10*, 67. doi:10.1186/1471-2288-10-67

Arns, M., Kleinnijenhuis, M., Fallahpour, K., & Breteler, R. (2008). Golf performance enhancement and real-life neurofeedback training using personalized event-locked EEG profiles. *Journal of Neurotherapy, 11*(4), 11-18.

Baker, T. L. (1994). *Doing social research*: New York: McGraw-Hill Inc.

Basar, E. (2013). Brain oscillations in neuropsychiatric disease. *Dialogues in clinical neuroscience, 15*(3), 291-300. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/24174901

Becerra, J., Fernandez, T., Harmony, T., Caballero, M. I., Garcia, F., Fernandez-Bouzas, A., . . . Prado-Alcala, R. A. (2006). Follow-up study of learning-disabled children treated with neurofeedback or placebo. *Clin EEG Neurosci, 37*(3), 198-203. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/16929704

Blumenstein, B., & Orbach, I. (2014). Biofeedback for Sport and Performance Enhancement. In: Oxford University Press.

Boekaerts, M., Pintrich, P. R., & Zeidner, M. (2005). *Handbook of Self-Regulation*: Elsevier Science.

Cheng, M. Y., Huang, C. J., Chang, Y. K., Koester, D., Schack, T., & Hung, T. M. (2015). Sensorimotor Rhythm Neurofeedback Enhances Golf Putting Performance. *J Sport Exerc Psychol, 37*(6), 626-636. doi:10.1123/jsep.2015-0166

Clarys, J. P., & Cabri, J. (1993). Electromyography and the study of sports movements: a review. *Journal of sports sciences, 11*(5), 379-448.

Cleary, T. J., & Zimmerman, B. J. (2001). Self-Regulation Differences during Athletic Practice by Experts, Non-Experts, and Novices. *Journal of Applied Sport Psychology, 13*(2), 185-206. doi:10.1080/104132001753149883

Cooke, A. M., Bellomo, E., Gallicchio, G., & Ring, C. (2018). Neurofeedback Research in Sport: A Critical Review of the Field. In *Handbook of Sport Neuroscience and Psychophysiology* (pp. 282-303): Routledge.

Cortoos, A., De Valck, E., Arns, M., Breteler, M. M., & Cluydts, R. (2010). An Exploratory Study on the Effects of Tele-neurofeedback and Tele-biofeedback on Objective and Subjective Sleep in Patients with Primary Insomnia. *Applied Psychophysiology and Biofeedback, 35*(2), 125-134. doi:10.1007/s10484-009-9116-z

Doppelmayr, M., & Weber, E. (2011). Effects of SMR and Theta/Beta Neurofeedback on Reaction Times, Spatial Abilities, and Creativity. *Journal of Neurotherapy, 15*(2), 115-129. doi:10.1080/10874208.2011.570689

Egner, T., & Gruzelier, J. H. (2001). Learned self-regulation of EEG frequency components affects attention and event-related brain potentials in humans. *Neuroreport, 12*(18), 4155-4159.

Egner, T., & Gruzelier, J. H. (2004). EEG biofeedback of low beta band components: frequency-specific effects on variables of attention and event-related brain potentials. *Clin Neurophysiol, 115*(1), 131-139.

Emmert, K., Kopel, R., Koush, Y., Maire, R., Senn, P., Van De Ville, D., & Haller, S. (2017). Continuous vs. intermittent neurofeedback to regulate auditory cortex activity of tinnitus patients using real-time fMRI - A pilot study. *Neuroimage Clin, 14*, 97-104. doi:10.1016/j.nicl.2016.12.023

Escolano, C., Aguilar, M., & Minguez, J. (2011). *EEG-based upper alpha neurofeedback training improves working memory performance.* Paper presented at the Engineering in medicine and biology society, EMBC, 2011 Annual International Conference of the IEEE.

Fovet, T., Jardri, R., & Linden, D. (2015). Current Issues in the Use of fMRI-Based Neurofeedback to Relieve Psychiatric Symptoms. *Curr Pharm Des, 21*(23), 3384-3394. doi:10.2174/1381612821666150619092540

French, S. N. (1978). Electromyographic biofeedback for tension control during gross motor skill acquisition. *Perceptual and motor skills, 47*(3), 883-889.

Gevensleben, H., Holl, B., Albrecht, B., Schlamp, D., Kratz, O., Studer, P., . . . Heinrich, H. (2010). Neurofeedback training in children with ADHD: 6-month follow-up of a randomised controlled trial. *Eur Child Adolesc Psychiatry, 19*(9), 715-724. doi:10.1007/s00787-010-0109-5

Ghaziri, J., & Thibault, R. T. (2019). Neurofeedback: An inside perspective. In *Casting Light on the Dark Side of Brain Imaging* (pp. 113-116): Elsevier.

Gluck, M. A., Mercado, E., & Myers, C. E. (2016). *Learning and Memory: From Brain to Behavior*: Worth Publishers.

Groppe, D. M., Bickel, S., Keller, C. J., Jain, S. K., Hwang, S. T., Harden, C., & Mehta, A. D. (2013). Dominant frequencies of resting human brain activity as measured by the electrocorticogram. *Neuroimage, 79*, 223-233. doi:10.1016/j.neuroimage.2013.04.044

Gruzelier, J. H. (2014). EEG-neurofeedback for optimising performance. I : a review of cognitive and affective outcome in healthy participants. *Neuroscience & Biobehavioral Reviews, 44*, 124-141.

Gruzelier, J. H., & Egner, T. (2004). Physiological self-regulation: Biofeedback and neurofeedback. In A. Williamon (Ed.), *Musical Excellence: Strategies and Techniques to Enhance Performance.* (pp. 197-219). London: Oxford University Press.

Guntensperger, D., Thuring, C., Meyer, M., Neff, P., & Kleinjung, T. (2017). Neurofeedback for Tinnitus Treatment - Review and Current Concepts. *Front Aging Neurosci, 9*, 386. doi:10.3389/fnagi.2017.00386

Halder, S., Varkuti, B., Bogdan, M., Kübler, A., Rosenstiel, W., Sitaram, R., & Birbaumer, N. (2013). Prediction of brain-computer interface aptitude from individual brain structure. *Frontiers in human neuroscience, 7*, 105. doi:10.3389/fnhum.2013.00105

Hall, J., & Stewart, M. E. (2010). Basic psychology. In E. C. Johnstone, D. C. Owens, S. M. Lawrie, A. M. McIntosh, & M. Sharpe (Eds.), *Companion to Psychiatric Studies* (pp. 95-108). St. Louis: Churchill Livingstone.

Hammond, D. C. (2011). What is Neurofeedback: An Update. *Journal of Neurotherapy, 15*(4), 305-336. doi:10.1080/10874208.2011.623090

Hashemian, P., Farrokhi, A., Mirifar, A., Keihani, M., & Sadjadi, A. (2013). The effect of neurofeedback training on attention rate in proficient track and field â athletics. *Journal of Fundamentals of Mental Health, 15*(60), 312-318.

Heatherton, T. F. (2011). Neuroscience of Self and Self-Regulation. *Annual review of psychology, 62*, 363-390. doi:10.1146/annurev.psych.121208.131616

Hulley, S. B., Cummings, S. R., Browner, W. S., Grady, D. G., & Newman, T. B. (2013). *Designing clinical research*: Lippincott Williams & Wilkins.

Hung, T. M., & Cheng, M. Y. (2018). Neurofeedback in Sport: Theory, Methods, Research, and Efficacy. In *Handbook of Sport Neuroscience and Psychophysiology* (pp. 304-319): Routledge.

Kamiya, J. (1962). *Conditioned discrimination of the EEG alpha rhythm in humans.* Paper presented at the the Western Psychological, San Francisco, California.

Kouijzer, M. E. J., de Moor, J. M. H., Gerrits, B. J. L., Buitelaar, J. K., & van Schie, H. T. (2009). Long-term effects of neurofeedback treatment in autism. *Research in Autism Spectrum Disorders, 3*(2), 496-501.

Kouijzer, M. E. J., de Moor, J. M. H., Gerrits, B. J. L., Congedo, M., & van Schie, H. T. (2009). Neurofeedback improves executive functioning in children with autism spectrum disorders. *Research in Autism Spectrum Disorders, 3*(1), 145-162.

Krizan, Z., & Hisler, G. (2016). The essential role of sleep in self-regulation. *Handbook of self-regulation (3rd ed.). New York, NY: Wiley.*

Landers, D. M., Petruzzello, S. J., Salazar, W., Crews, D. J., Kubitz, K. A., Gannon, T. L., & Han, M. (1991). The influence of electrocortical biofeedback on performance in pre-elite archers. *Med Sci Sports Exerc, 23*(1), 123-129. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1997806

Linden, D. E., & Turner, D. L. (2016). Real-time functional magnetic resonance imaging neurofeedback in motor neurorehabilitation. *Curr Opin Neurol, 29*(4), 412-418. doi:10.1097/wco.0000000000000340

Mihara, M., Hattori, N., Hatakenaka, M., Yagura, H., Kawano, T., Hino, T., & Miyai, I. (2013). Near-infrared spectroscopy-mediated neurofeedback enhances efficacy of motor imagery-based training in poststroke victims: a pilot study. *Stroke, 44*(4), 1091-1098. doi:10.1161/strokeaha.111.674507

Miller, N. E. (1978). Biofeedback and Visceral Learning. *Annual review of psychology, 29*(1), 373-404. doi:10.1146/annurev.ps.29.020178.002105

Miller, N. E., & DiCara, L. (1967). Instrumental learning of heart rate changes in curarized rats: shaping, and specificity to discriminative stimulus. *J Comp Physiol Psychol, 63*(1), 12-19. doi:10.1037/h0024160

Morgan, S. J., & Mora, J. A. M. (2017). Effect of Heart Rate Variability Biofeedback on Sport Performance, a Systematic Review. *Applied Psychophysiology and Biofeedback*, 1-11.

Petruzzello, S. J., Landers, D. M., & Salazar, W. (1991). Biofeedback and sport/exercise performance: Applications and limitations. *Behavior therapy, 22*(3), 379-392.

Reiner, M., Gruzelier, J. H., Bamidis, P. D., & Auer, T. (2018). The Science of Neurofeedback: Learnability and Effects. *Neuroscience, 378*, 1-10. doi:https://doi.org/10.1016/j.neuroscience.2018.04.024

Rogala, J., Jurewicz, K., Paluch, K., Kublik, E., Cetnarski, R., & Wróbel, A. (2016). The do's and don'ts of neurofeedback training: A review of the controlled studies using healthy adults. *Frontiers in human neuroscience, 10*(JUNE2016), 301. doi:10.3389/fnhum.2016.00301

Sanei, S., & Chambers, J. A. (2007). *EEG signal processing*: John Wiley & Sons.

Schabus, M. (2017). Reply: On assessing neurofeedback effects: should double-blind replace neurophysiological mechanisms? *Brain, 140*(10), e64-e64. doi:10.1093/brain/awx212

Schabus, M. (2018). Reply: Noisy but not placebo: defining metrics for effects of neurofeedback. *Brain, 141*(5), e41-e41. doi:10.1093/brain/awy061

Sitaram, R., Ros, T., Stoeckel, L., Haller, S., Scharnowski, F., Lewis-Peacock, J., . . . Sulzer, J. (2017). Closed-loop brain training: the science of neurofeedback. *Nat Rev Neurosci, 18*(2), 86-100. doi:10.1038/nrn.2016.164

Strehl, U., Birkle, S. M., Worz, S., & Kotchoubey, B. (2014). Sustained reduction of seizures in patients with intractable epilepsy after self-regulation training of slow cortical potentials - 10 years after. *Frontiers in human neuroscience, 8*, 604. doi:10.3389/fnhum.2014.00604

Tan, G., Thornby, J., Hammond, D. C., Strehl, U., Canady, B., Arnemann, K., & Kaiser, D. A. (2009). Meta-analysis of EEG biofeedback in treating epilepsy. *Clinical EEG and Neuroscience, 40*(3), 173-179.

Thibault, R. T., Lifshitz, M., Birbaumer, N., & Raz, A. (2015). Neurofeedback, Self-Regulation, and Brain Imaging: Clinical Science and Fad in the Service of Mental Disorders. *Psychother Psychosom, 84*(4), 193-207. doi:10.1159/000371714

Thibault, R. T., Lifshitz, M., & Raz, A. (2016). The self-regulating brain and neurofeedback: Experimental science and clinical promise. *Cortex, 74*, 247-261. doi:10.1016/j.cortex.2015.10.024

Thibault, R. T., & Raz, A. (2017). The psychology of neurofeedback: Clinical intervention even if applied placebo. *Am Psychol, 72*(7), 679-688. doi:10.1037/amp0000118

van Teijlingen, E., & Hundley, V. (2002). The importance of pilot studies. *Nurs Stand, 16*(40), 33-36. doi:10.7748/ns2002.06.16.40.33.c3214

Vernon, D. (2005). Can neurofeedback training enhance performance? An evaluation of the evidence with implications for future research. *Applied Psychophysiology and Biofeedback, 30*(4), 347-364.

Wang, T., Mantini, D., & Gillebert, C. R. (2018). The potential of real-time fMRI neurofeedback for stroke rehabilitation: A systematic review. *Cortex, 107*, 148-165. doi:10.1016/j.cortex.2017.09.006

Weber, E., Köberl, A., Frank, S., & Doppelmayr, M. (2011). Predicting successful learning of SMR neurofeedback in healthy participants: methodological considerations. *Applied Psychophysiology and Biofeedback, 36*(1), 37-45.

Weinberg, R. S., & Hunt, V. V. (1976). The interrelationships between anxiety, motor performance and electromyography. *Journal of Motor Behavior, 8*(3), 219-224.

Witte, M., Kober, S. E., & Wood, G. (2018). Noisy but not placebo: defining metrics for effects of neurofeedback. *Brain*.

Wyrwicka, W., & Sterman, M. B. (1968). Instrumental conditioning of sensorimotor cortex EEG spindles in the waking cat. *Physiology & behavior, 3*(5), 703-707.

Zagha, E., & McCormick, D. A. (2014). Neural control of brain state. *Curr Opin Neurobiol, 29*, 178-186. doi:10.1016/j.conb.2014.09.010

Zaichkowsky, L. (1983). The use of biofeedback for self-regulation of performance states. *The mental aspects of gymnastics*, 95-105.

Zeichkowsky, L. D. (1975). *Combating stress. What about relaxation training and biofeedback*: APAPQ.

Zoefel, B., Huster, R. J., & Herrmann, C. S. (2011). Neurofeedback training of the upper alpha frequency band in EEG improves cognitive performance. *Neuroimage, 54*(2), 1427-1431. doi:10.1016/j.neuroimage.2010.08.078

Appendix

List of Publications and Submissions

* Indicating corresponding author

Mirifar, A.*, Keil, A., Beckmann, J., & Ehrlenspiel, F. (ready for submission). Neurofeedback and neural self-regulation: Evidence and Challenges.

Mirifar, A.*, Cross-Villasana, F., Ehrlenspiel, F. & Beckmann, J. (under 2nd round of review). Effects of the Unilateral Dynamic Handgrip on Resting Cortical Activity Levels: A Replication and Extension, *International Journal of Psychophysiology*

Erk, W., **Mirifar**, A., Luan, M., & Beckmann, J. (under 2nd round of review). Dealing with Failure: Prefrontal Asymmetry Predicts Affective Recovery and Cognitive Performance. *Biological Psychology*

Luan, M., **Mirifar**, A., Beckmann, J., & Ehrlenspiel, F. (under review). Multisensory action effects facilitate the performance of motor sequences. *Attention, Perception, & Psychophysics*

Luan, M., **Mirifar**, A., Beckmann, J., & Ehrlenspiel, F. (under review). Differential effects of dual-tasks across learning a finger sequence.

Mirifar, A.*, Keil, A., Beckmann, J., & Ehrlenspiel, F. (2018). No Effects of Neurofeedback of Beta Band Components on Reaction Time Performance. *Journal of Cognitive Enhancement* 3, no. 3 (2019): 251-260.

Mirifar, A.*, Beckmann, J., & Ehrlenspiel, F. (2017). Neurofeedback as supplementary training for optimizing athletes' performance: A systematic review with implications for future research. *Neuroscience & Biobehavioral Reviews*, 75, 419-432.

Hashemian, P., Farrokhi, A., **Mirifar**, A.*, Keihani, M., & Sadjadi, A. (2014). The effect of neurofeedback training on attention rate in proficient track and field athletics. *Journal of Fundamentals of Mental Health*, 15, (60) [persian]

Farokhi, A., Hashemian, P., **Mirifar**, A.*, Keihani, M., & Kaikhavani, S. (2013). The effect of neurofeedback training on the trait-competitive anxiety of athletes, *Journal of Ilam University of Medical Sciences*, 21 (2), 21-27. [persian]

Keihani M, **Mirifar** A*, Hashemian P, & Farrokhi A. (2013). The effect of neurofeedback training on competitive state- anxiety in track and field athletics. *Journal of Fundamentals of Mental Health*, 15 (59), 224-231[persian]

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

Author: Arash Mirifar,Jürgen Beckmann,Felix Ehrlenspiel

Publication: Neuroscience & Biobehavioral Reviews

Publisher: Elsevier

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