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APPLICATION OF NEUROFEEDBACK DEVICES IN COGNITIVE PERFORMANCE ENHANCEMENT AND TRACKING LEARNING PATTERNS IN SPORTS

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Abstract
We examined the current research and studies regarding the neurofeedback trainings, including neurofeedback protocols and available technologies and devices. The results show that neurofeedback training can enhance effectively the cognitive abilities of athletes such as, attention, concentration, reaction time, stress tolerance, and mental toughness. The results may provide helpful information for practitioner specialists and researchers in the applied field.

Keywords*: neurofeedback, cognitive performance, learning patterns*

INTRODUCTION

The integration of cognitive science with sports training, represents a promising boundary for performance optimization through targeted neural adaptations and skill acquisition pathways. This review primarily aims to introduce the importance of neurofeedback trainings, and the different devices and techniques which can be applied in different sports. Secondly to synthesize the current research on cognitive training methodologies, neurostimulation techniques, and learning assessment tools that can be applied across sports domains where complex decisions have to be made to optimize athletic performance.

THEORETICAL BACKGROUND

The EEG biofeedback, better known as Neurofeedback, is a methodology which allows the individuals to receive real-time feedback on their brain activities and helps them to learn how to influence certain brain waves consciously. This method is based on electroencephalography (EEG), which detects and measures the brain's electrical signals. During neurofeedback training sessions, athletes receive visual or auditory feedback in connection with their brain activity, to learn how to reach the desired brain states (GONG et al., 2021).

Competitive sports place particularly high cognitive demands on athletes, since a successful performance not only depends on physical abilities, but also on rapid reaction times, precise spatial orientation, divided attention, and complex decision-making processes. The best example is the race car drivers, who must interpret complex information and make decisions under extreme pressure in fractions of a second (HORVÁTH et al., 2022).

Neurofeedback essentially helps the athletes to develop the self-regulation ability of their brains. The psychomotor efficiency hypothesis suggests that neurofeedback optimizes the brain functions, which leads to the improvement both of the motoric performances and the cognitive functions of the individuals. Research indicates that the sensorimotor rhythm and the frontal midline theta are the keys for concentration and relaxation (CHENG et al., 2024).

The regular usage of Neurofeedback can improve the psychophysical balance, thus the performance of athletes. Several studies confirm that, after the neurofeedback training, the performance of the athletes have been improved alongside with the task concentration, also showed better emotional control, and their mental toughness have been increased (TORMA - BALOGH, 2024).

LEARNING PATTERNS AND MECHANISMS

During the application of the neurofeedback trainings, different learning patterns and mechanisms can be observed to improve the performance of the athletes. One of them is the implicit learning, this refers to learning without intention. In implicit learning, a permanent modification of the organism's activity resulting from its interactions with the external environment in the absence of intention and awareness about the learning materials and methods (VINTER et al., 2010).

Another mechanism is the Operant conditioning. Operant conditioning is a method of learning, that uses rewards and punishment to modify the behaviour. The Infra Low Frequency Neurofeedback method is a learning theory-based method, in which the device is teaching the correct state to the brain, and the basis of this method is the operant conditioning. During this method the positive feedback reinforces the desired brain activity patterns (KIRK et al., 2022).

During neurofeedback trainings another mechanism can be detected known as Transfer effect. The skills acquired during neurofeedback trainings, such as concentration or emotional regulation, can be transferred to competition scenarios, where the athletes automatically apply these skills without any conscious thought (GONG et al., 2021).

COGNITIVE PERFORMANCE ENHANCEMENT THROUGH NEUROFEEDBACK

One of the main advantages of the neurofeedback training is the ability to develop various cognitive skills effectively, which are critical for a successful high performance. These areas are presented in detail in this section.

Attention and concentration: Attention and concentration are outstandingly crucial in sports, where the athlete must monitor their environment continuously, while accomplishing complex tasks. Neurofeedback can improve these abilities, since they are teaching athletes, how to maintain attentional focus for longer periods and how to exclude distractions (CORRADO et al., 2024).

In case of the race car drivers, neurofeedback can be particularly useful, as during the race they must process plenty amount of visual and auditory information, while manoeuvring at high speed. For example, the light-based reaction agility training can improve significantly their visual orientation performance, and their selective visual attention, which was provided by their shorter reaction times in the Visual Pursuit Test (LVT) (HORVÁTH et al., 2022).

Reaction time and decision-making: According to the cognitive test of Vienna Test System (VTS), race car drivers who went through neurofeedback trainings, responded faster and more accurate to the tasks of Stroop test, which means they had a better cognitive flexibility and switching ability. In addition, improvements were observed in the Determination Test (DT), which measures reactive stress tolerance and reaction speed in response to rapidly changing stimuli (HORVÁTH et al., 2022).

Another study compered the neuroMoon (nM) and NeuroTracker (NT) neurofeedback systems. The study showed that participants had faster reaction times in both, colour naming and word reading conditions in the Stroop test, and also a faster working time and average reaction time in the task switching test after neurofeedback training (HORVÁTH et al., 2023).

Stress management and Emotional regulation: In competitive sports on of the greatest challenges is managing stress and performance anxiety. Neurofeedback can stabilize the mood of the athletes and their emotional responses, including their perception and stress management abilities. It can reduce the anxiety and helping them to avoid paralyzing for any second, which can cripple their performance. Although it may inhibit the perception of the athlete, in fact, it may sharpen it, allowing a healthy motivation to support optimal performance without any emotional overload (ROBAZZA et. al., 2023).

Research among elite youth fencers showed that the mental toughness and stress tolerance improved after neurofeedback training. Based on the data of the Electro gastrographic Stress Holter, the heart rate increased less in response to stress after neurofeedback training, which indicates improved stress management (TORMA – BALOGH, 2024).

NEUROFEEDBACK PROTOCOLS AND TECHNOLOGICAL DEVICES

An effective neurofeedback training requires the understanding of the different protocols and technological solutions, which are available to athletes and coaches. The neurofeedback trainings can be very different depending on the frequency and duration of the trainings of athletes, the method of the feedback, and on the targeted brain waves. The most common protocol used in sports are the followings:

Sensomotor rhythm training (SMR): This focuses on the beta waves in the 12-15 Hz range. This is associated with calm awareness and the motoric control. This protocol can improve the motoric coordination and precision (CHENG et al., 2024).

Beta training: Regulating the higher beta waves (15-20 Hz) can help the athletes to improve their attentional focus and concentration, it is particularly important for those athletes who have to maintain intense focus for an extended period (LUNINA et al., 2024).

Reactive agility training: This uses light-based stimuli, to improve reaction time, visual perception and decision-making (HORVÁTH et al., 2022).

Neurofeedback trainings usually last 6-12 weeks, with 2-3 weekly sessions, each lasting about 30-60 minutes. The frequency and duration of the trainings must be in alignment with the athletes' individual needs and their fixture (TORMA – BALOGH, 2024).

Regarding the technical abilities and devices, various technological solutions are available, offering different levels of accuracy and user experience

The most accurate device, featuring multiple electrodes and very detailed EEG data, is the Clinical EEG system. These are suitable for professional athletes, the downsides are that these are very expensive and requires trained personal for usage. Portable EEG devices like the Muse 2 EEG, are easier to use, they are portable and relatively affordable. However, on the downside, these devices are less accurate than the clinical ones, although, more suitable for daily trainings (TORMA – BALOGH, 2024). Also, on the market exists neurofeedback games and applications, which provides feedback in a gamified format, that increases the motivation and engagement of the user. Such a software is for example the neuroMoon (nM) and NeuroTracker (NT) systems (HORVÁTH et. al., 2023). The last kind of training device is the Reactive agility training devices, for example the Witty SEM visual reaction test device, which uses LED lights to increase the reaction time and decision-making of the athletes (VASILE et al., 2024).

Selecting the appropriate device, it must be taken into consideration the need of the athlete, the specific requirements of the sport, the available resources and the professional support (TOSTI et al., 2024).

RESEARCH METHODOLOGY

This scoping review follows the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) guidelines (TRICCO et al., 2018). The methodological framework is based on Arksey and O'Malley's approach as refined by the Joanna Briggs Institute (ARKSEY – O'MALLEY, 2005). A comprehensive search was conducted across multiple electronic databases including PubMed, Semantic

Scholar, and Google Scholar. The search was limited to articles published between January 2015 and April 2025. Regarding the search terms, the following terms were used in various combinations: "athletes," "sports," "players," "performers" "neurofeedback," "EEG feedback," "brain-computer interface," "BCI," "neuromodulation" "cognitive performance," "attention," "concentration," "motor learning," "skill acquisition," "peak performance," "learning patterns". Regarding the selection process, the eligibility criteria was the following. We included the studies which were investigating neurofeedback training or devices in athletic or sports contexts, research focusing on cognitive performance enhancement or learning patterns, peer-reviewed articles published in English, studies reporting outcomes related to performance, cognitive function, or learning. The studies had to be published between January 2015 and April 2025. We were excluding studies which were focusing solely on clinical populations (e.g., ADHD, epilepsy), conference abstracts without full-text availability, opinion papers or commentaries without original data, studies which were not reporting cognitive or performance outcomes and studies which were focusing exclusively on physiological outcomes without cognitive measures.

The selection process involved two phases (Figure 1). During the first phase we were screening the titles and abstracts for relevance according to the inclusion and exclusion criteria. In the second phase full-text articles of potentially eligible studies were retrieved and assessed for final inclusion. The selection process followed the PRISMA-ScR guidelines and is illustrated in the flow diagram. Data from included studies were extracted using a standardized form that captured study characteristics (authors, year, country, study design), participant characteristics (sample size, type of athletes, experience level), neurofeedback protocol, and outcome measures.

The search yielded 127 potentially relevant citations. After removing duplicates (n=28), 99 articles underwent title and abstract screening, resulting in 45 articles for full-text review. After applying inclusion and exclusion criteria, 25 articles were included in the final analysis. The PRISMA-ScR flow diagram detailing the selection process.

The 25 included studies comprised 18 experimental studies, 4 quasi-experimental designs, 2 systematic reviews, and 1 meta-analysis. Sample sizes ranged from 10 to 60 participants (median: 27). Studies focused on various sports: precision sports (shooting, archery; n=8), team sports (n=5), individual sports (golf, tennis; n=7), and general athletic populations (n=5).

Most studies (n=20) used EEG-based neurofeedback, while the remaining studies employed functional near-infrared spectroscopy (fNIRS) or combined EEG with other biofeedback modalities. Neurofeedback protocols primarily targeted frontal-midline theta (4-8 Hz), sensorimotor rhythm (SMR; 12-15 Hz), alpha (8-13 Hz), and beta (13-30 Hz) frequency bands.

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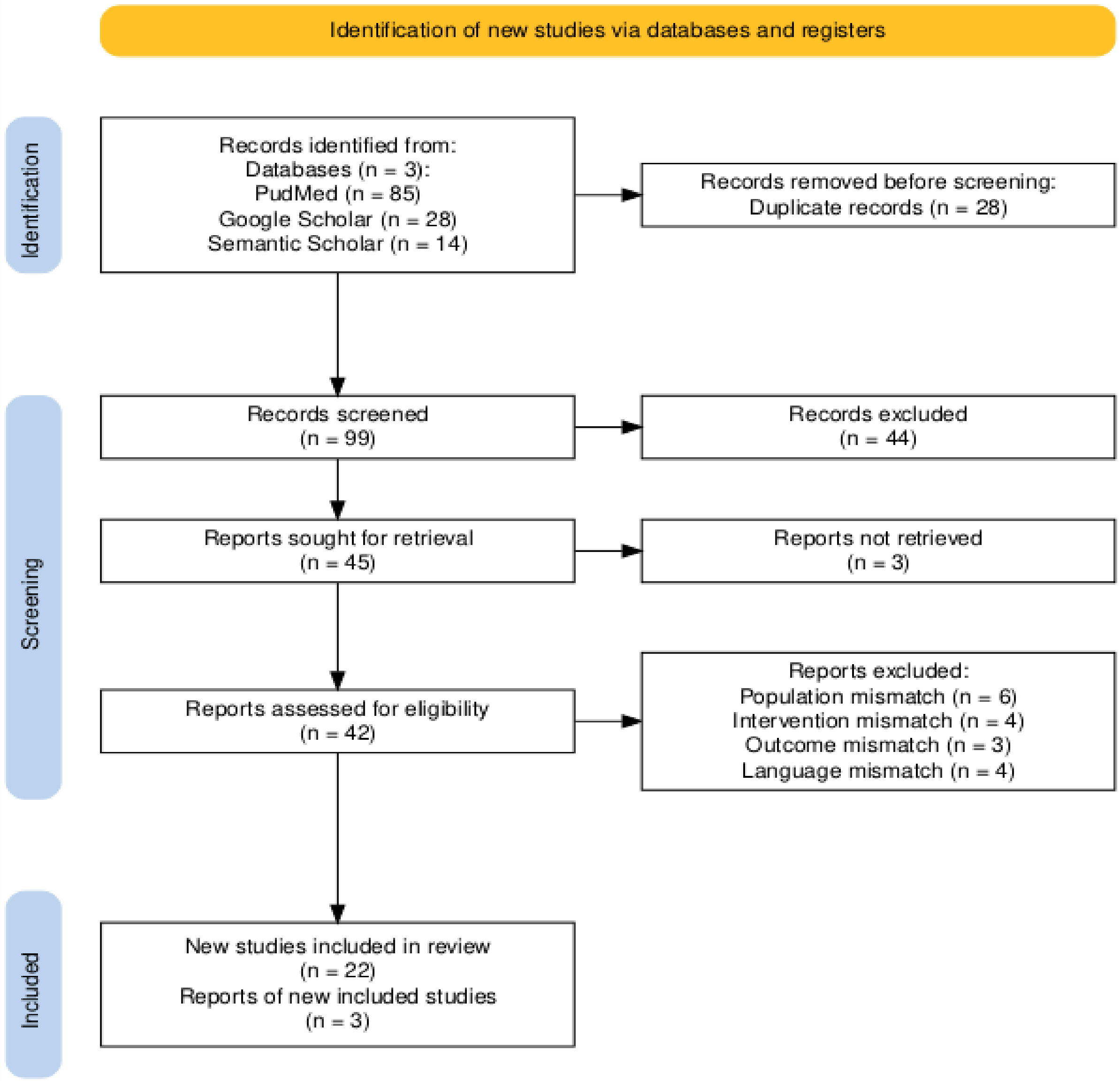

Figure 1: PRISMA flow chart showing the selection process of the studies according to the inclusion and exclusion criteria of this scoping review.

LIMITATIONS

It is important to recognize the various limitations of this scoping review. First it is possible that pertinent studies were overlooked due to the search strategy's lack of systematicity. We might have overlooked literature published in journals not indexed in these databases or using different terminology if we had concentrated on databases and search terms.

Second, there may be linguistic bias introduced by including only English-language publications, which could lead to the exclusion of important research that have been published in other languages.

Third, it is difficult to draw firm conclusions about best practices due to the diversity of neurofeedback protocols, outcome measures, and study designs, which hinders direct comparisons.

Fourth, we admit that our non-systematic search strategy may introduce selection bias. Our emphasis on peer-reviewed, published research may have overestimated the efficacy of neurofeedback interventions by omitting important information from unpublished or unfavourable study results.

Finally, although we made an effort to evaluate study quality using the CRED-nf checklist, thorough quality assessment was challenging due to the variations in reporting standards amongst studies.

DISCUSSION

During the research we applied a thematic analysis methodology, which allowed us to identify patterns across studies. The analysis yielded four main themes.

I. Neurofeedback Protocols and Enhancement of Cognitive Control. Studies examining cognitive control mechanisms revealed that frontal-midline theta neurofeedback training was associated with improvements in working memory and attentional control (ESCHMANN et al., 2022; NAN et al., 2015). Nonetheless, it seemed that the transfer effects were unique to forms of cognitive control. According to one study, neurofeedback training improved anticipatory attention, or proactive control, but not response inhibition, or reactive control (ESCHMANN – MECKLINGER, 2022). Given this specificity, neurofeedback protocols ought to be customized to target the cognitive control type most pertinent to the sport in question. In precision sports like shooting and archery, protocols focusing on sensorimotor rhythm (SMR) enhancement produced the most consistent improvements in attention and performance (CORRADO et al., 2024). For instance, shooters who received neurofeedback-EEG training aimed at enhancing beta frequency (12–22 Hz) showed enhanced accuracy and speed in their attentional performance (CORRADO et al., 2024).

II. Individual Differences in Neurofeedback Learning. The variation in people's capacity to learn from neurofeedback was a noteworthy trend amongst studies. Research distinguished between "responders" who were able to effectively control their brain activity during training and "non-responders" who had difficulty achieving self-regulation (ESCHMANN et al., 2022; NAN et al., 2015). One study found that responders showed better motor performance and flow experience after a single 30-minute session of frontal-midline theta neurofeedback training compared to non-responders (ESCHMANN et al., 2022). Another study identified that resting and initial beta amplitudes could predict learning ability in beta/theta ratio neurofeedback training (Nan et al., 2015), suggesting that baseline EEG characteristics might serve as predictors of neurofeedback success. This individual variability highlights the importance of identifying factors that predict neurofeedback learning aptitude, which could help develop personalized protocols that maximize effectiveness across different athletes.

III. Function-Specific Instruction Approaches. An emerging trend in neurofeedback research is the development of function-specific instruction (FSI) approaches to provide participants with targeted verbal instructions to enhance control over specific EEG parameters (WANG et al., 2023). This contrasts with conventional teaching methods, which generally emphasize focus or relaxation. According to a study that compared FSI with conventional instruction in visuomotor skill performance, FSI produced better results in terms of improving visuomotor performance and modulating mu rhythm (WANG et al., 2023). This implies that, especially for sports applications where mental states correlate to optimal performance, the instructional component of neurofeedback training may be just as significant as the technical aspects of the protocol itself.

IV. Long-Term Effects and Transfer to Performance. Although the immediate post-training effects were promising, there were conflicting findings regarding the long-term sustainability and transfer of neurofeedback benefits to actual sports performance (MIKICIN et al., 2015). According to certain research, there were notable gains in cognitive and motor abilities that continued at follow-up evaluations (ESCHMANN – MECKLINGER, 2022). A meta-analysis revealed a moderate positive effect of neurofeedback training on sport motor tasks (Hedges's g = 0.78, 95% CI: 0.49–1.07) (YU et al., 2015). Crucially, research with higher methodological quality scores showed more consistent and significant effects, indicating that carefully thought-out protocols are essential to getting significant results.

Few studies have looked at how laboratory-based neurofeedback enhancements translate to actual competitive performance, making transfer to competition settings an understudied area (CORRADO et al., 2024).

Different neurofeedback protocols target distinct cognitive processes, and the selection should be tailored to the specific cognitive demands of the sport (ESCHMANN – MECKLINGER, 2022). Substantial differences exist in individual's ability to learn from neurofeedback, suggesting the need for personalized approaches and potentially screening methods to identify likely responders (NAN et al., 2015). The way instructions are presented may significantly impact training outcomes, with function-specific instructions showing promise (WANG et al., 2023). Studies with higher methodological quality demonstrated more consistent effects, emphasizing the importance of well-designed protocols and appropriate control conditions (YU et al., 2025). Research tracking learning patterns during neurofeedback training remains relatively limited, though some studies have begun to characterize the learning curves and identify predictive factors of successful skill acquisition (NAN et al., 2015). The integration of neurofeedback with other training techniques, such as motor imagery or biofeedback, appears to be a promising direction for maximizing effectiveness (CORRADO et al., 2024).

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