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The Effect of Neurofeedback Training on Improving Executive Functions in Student Athletes

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Quantitative Study

Abstract

Background: Executive functions can be viewed as a key indicator of how and when we perform routine behaviors. They help individuals set goals, regulate themselves, inhibit inappropriate responses, remain flexible, and focus on future-oriented actions. The aim of this study was to determine the effect of neurofeedback training on improving executive functions (working memory, cognitive flexibility, and sustained attention) in student athletes.

Methods: This study used a quasi-experimental design, with the research being applied in nature and employing a pre-test/post-test control group desighn. The population consisted of 200 middle school students (aged 12 to 15 yr) in Shahroud. For sampling, 20 student athletes were first selected based on the results of a physical activity questionnaire and were then randomly assigned to either the experimental or control group. The experimental group underwent 13 neurofeedback training sessions (aimed at increasing beta waves, decreasing theta waves, and enhancing alpha waves), with three sessions per week, each lasting 30 minutes. The control group received no intervention. The research tools included the N-Back test, Wisconsin Card Sorting Test, and Continuous Performance Test to measure working memory, cognitive flexibility, and sustained attention, respectively.

Results: The results of the two-way mixed ANOVA (2x2) indicated a significant difference between the experimental and control groups after controlling for the pre-test effect. According to the LSD post-hoc test, there was no significant difference between the experimental and control groups in the variables of working memory and sustained attention, while a significant difference was observed in cognitive flexibility. Further within-group comparisons, using repeated measures ANOVA, revealed no significant differences in any of the three variables between the groups.

Conclusion: Neurofeedback seems capable of retraining brainwave activity to enhance athletic performance and improve certain mental and cognitive abilities, such as adaptability to changing conditions. However, neurofeedback training in healthy individuals requires further comprehensive research.

Keywords: Neurofeedback; Working memory; Cognitive flexibility; Sustained attention; Athlete

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Introduction

Executive functions refer to higher-level cognitive processes that enable flexible regulation, monitoring of goal-directed behaviors, and thoughts by controlling lower-level cognitive processes, particularly in new or complex situations (Friedman & Robbins, 2022; MacPherson, Gillebert, Robinson, & Vallesi, 2019; Vallesi, 2021). They play a role in the activation and control of conscious perception, emotions, thoughts, and actions (Gordon et al., 2020). According to information processing theory, there are two mechanisms: higher-level and lower-level schemas. Higher-level schemas represent problem-solving, while lower-level schemas determine actions. Schemas guide a person's actions or thoughts based on environmental conditions. When a person encounters a routine, everyday situation, their established schema automatically responds, preventing inappropriate actions for that situation. However, in unusual or non-routine circumstances, the supervisory attention system is utilized to handle the new situation (Hunter & Sparrow, 2012). Attention control, a key element, helps monitor deliberate planning and awareness of actions appropriate for new situations that cannot be solved by previously learned programs, or when it is crucial to avoid mistakes or typical responses. Therefore, executive functions are especially activated when focus and attention are required in unexpected, challenging, or complex environments (Moore et al., 2019), helping individuals recognize unforeseen situations and quickly design strategies and plans (Mary et al., 2016).

Executive functions include various components, and among the most important ones examined in the present study are working memory, cognitive flexibility, and sustained attention. Working memory is a part of the human memory system responsible for simultaneously processing and storing incoming information, and it even operates in tasks that do not require explicit memory (Kreither, Papaioannou, & Luck, 2022). In other words, it is the center of thought, responsible for encoding, maintaining, or retaining, and manipulating cognitive representations of stimuli (Baddeley, 2000). Activities such as developing new strategies, calculating solutions to mathematical problems, and reading comprehension all take place there (Mosalman, Sohrabi, & Dadjoo, 2019). The importance of working memory lies in its ability to temporarily store and expand the content of memory, constantly adapting to meet simultaneous demands. Rather than replacing old information with new, this adaptation often involves updating old information in comparison with new data (Carretti, Cornoldi, De Beni, & Romanò, 2005), allowing individuals to keep the necessary data active for completing tasks (Cowan, 2016). This part of memory has a limited capacity, interacts with other executive functions, and its enhancement can lead to improvements in other components (Hughes & Russell, 1993).

Another component of executive functions is cognitive flexibility, which refers to an individual's ability to assess how controllable a situation is, and this assessment can change in different contexts. In other words, cognitive flexibility is the ability to adjust cognitive processes to confront new and unpredictable situations, and it results from flexible thinking (Carbonella & Timpano, 2016). People with flexible thinking use alternative explanations, positively reframe their mindset, and accept challenging situations or stressful events (Phillips, 2011). In contrast, individuals with lower cognitive flexibility find it difficult to forget their initial learning, insist on previous learning with negative consequences, and this hinders their adaptation to new academic and social conditions (Carbonella & Timpano, 2016).

The last and one of the most important cognitive aspects is attention, which is recognized as focus and alertness and is divided into selective attention, devided attention, shifting attention, and sustain attention (Davis, 2010). Vigilance or alertness is the most basic and simplest level of attention, upon which other types of attention rely (Wilson, 2002), playing an irreplaceable role in daily human life. For example, it refers to long-term focus and is generally associated with alertness (Cohen & Cohen, 2014). This type of attention is characterized by the ability to detect rare and unpredictable signals over a long period (Munir, Cornish, & Wilding, 2000) and involves maintaining a steady behavioral response to task-relevant stimuli during continuous and repetitive activity (Robertson, 1997 quoted in Huang, 2023).

Many studies claim that cognitive performance, such as memory, executive functions, sustained attention (Gruzelier, 2014), orientation and executive attention, P300b, spatial rotation, reaction time, complex psychomotor skills, implicit procedural memory, recognition memory, perceptual binding, intelligence, mood, and well-being (Gruzelier, 2014), can be improved throughout life using various methods like neurofeedback. Neurofeedback is a non-invasive approach in neuroscience that uses a closed loop between the brain and a computer with a five-element processing pipeline (Smit, 2024) (Figure 1).

The neurofeedback training system (NFT) receives brainwave activities from the electroencephalogram (EEG) amplifier and then extracts EEG features to define cognitive states. This system visualizes the estimated cognitive states for subjects who can recognize their current cognitive states (Duric, Assmus, Gundersen, & Elgen, 2012). In other words, neurofeedback/EEG measures a specific parameter of brain activity, which is presented to the individual in real-time through visual or auditory feedback. The individual's goal in this situation is to modify this parameter, thereby achieving self-regulation of brain activity (Deiber et al., 2021; Duric et al., 2012).

Brainwaves, which vary in function and frequency, include delta, theta, alpha, and beta waves. Delta waves range from 0.5 to 4 Hz and are seen during sleep at frequencies below 1 Hz, produced directly in the cortex, and apparently reflect cortical reorganization during the wake-sleep cycle (Doebel, 2020). Theta (θ) waves range from 4 to 8 Hz and play a role in cortical processing, as noted by Eisma et al. (Smit, 2024). Healthy individuals show an increase in theta waves in the cortical processing regions of the brain during encoding, maintenance, and retrieval of information (Hammond, 2011), as well as in tasks involving executive functions, such as set shifting (McCowan et al., 2021), updating working memory (Mizuhara & Yamaguchi, 2007), response inhibition (Harmony et al., 2009), and conflict monitoring, as cited in (Smit, 2024).

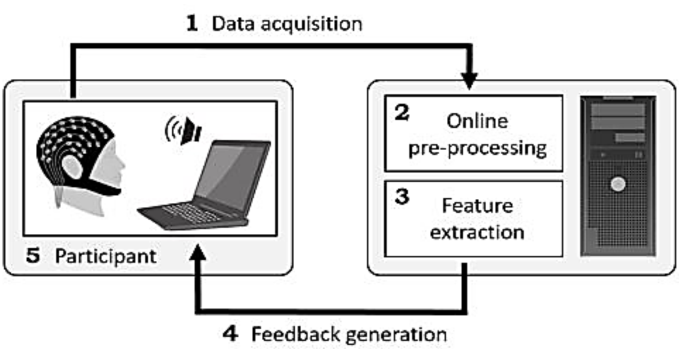

Figure 1. Neurofeedback processing pipeline

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Alpha waves range from 8 to 12 Hz and are associated with sensory processing, attention (Groppe et al., 2013), working memory, and inhibitory control (Cooper et al., 2003) as cited in (Viviani & Vallesi, 2021). Alpha activity is typically observed in a relaxed state when the eyes are closed (Hammond, 2011). Beta waves encompass all frequencies above 13 Hz, with beta rhythms at 15 to 18 Hz linked to focus and cognitive processing (Doebel, 2020; Hammond, 2011).

Neurofeedback training has shown strong findings in both health (Marzbani, Marateb, & Mansourian, 2016) and cognitive performance (Cross, Acquah, & Ramsey, 2014), as cited in (Domingos, Alves, Sousa, Rosa, & Pereira, 2020). Engelbrecht and colleagues evaluated the short- and long-term effects of frontal beta neurofeedback in healthy individuals and found that frontal beta frequency activity increased after 15 sessions of 45-minute neurofeedback interventions, and these effects remained stable for at least 3 years (Engelbregt et al., 2016). In athletes, neurofeedback can be used as a supplement to training and can improve parameters such as reaction time (Domingos et al., 2020). For example, in a beta1/theta experimental protocol to enhance focus and limit attention in skilled judo athletes, significant changes in their readiness for sports competitions were observed, with the most notable changes in reaction time occurring between the fourth and fifth weeks of training (Krawczyk, Kowalczyk, Żak, Daros, & Gozdowski, 2019).

In this context, distinct differences in the cortical activity of expert and novice athletes have been observed (Vernon, 2005), which aligns with the neural efficiency hypothesis (Babiloni et al., 2010). This hypothesis suggests that specific brain regions are activated for a particular task while irrelevant areas are deactivated during the same task (Domingos et al., 2020), as cited in (Haier, Siegel, Tang, Abel, & Buchsbaum, 1992). Jeunet and colleagues conducted a study aimed at identifying the neurophysiological (EEG) correlations of covert visuospatial attention (CVSA) in soccer goalkeepers, finding a significant positive correlation between the improvement in athletes' CVSA ability and the increase in their resting alpha power (Jeunet et al., 2020).

Data from karate athletes revealed that elite athletes, compared to amateurs, experienced less pronounced event-related alpha desynchronization (ERD) during performance, reinforcing the common idea that elite athletes utilize specialized brain areas for specific tasks (Babiloni et al., 2010). Given this, could neurofeedback training (increasing beta, reducing theta, and enhancing alpha) improve executive functions (working memory, cognitive flexibility, and sustained attention) in student athletes?

Methods

This study is quasi-experimental, applied in terms of its objective, and follows a within-group design with a pre-test, post-test format and a control group. The statistical population consisted of 200 secondary school students (ages 12 to 15) from Najabat, Besharat, Abu Dhar Ghafari, and Zeinab schools in Shahrood, who were randomly selected and completed the Physical Activity Questionnaire. The sample size was estimated using GPower software based on a between-group factorial design (2 groups) and a within-group factor (2 measurement phases), with a small to medium effect size (0.25), an alpha level of 0.05, and a power of 0.80, yielding 20 participants. Based on the questionnaire results, 20 student-athletes were selected, and from them, 10 were randomly assigned to the experimental group and 10 to the control group.

The participants were informed about the study protocol and procedures, all participated voluntarily, and the researcher committed to protecting their private and personal information. This study received ethical approval with the code IR.SSRC.REC.1401.134 from the Ethics Committee of the Institute of Physical Education and Sports Sciences.

The first step in conducting the research was administering the pre-test, where the N-Back test, the Wisconsin Card Sorting Test, and the Continuous Performance Test were used to measure working memory, cognitive flexibility, and sustained attention, respectively. Then, the experimental group entered the intervention phase. Initially, with longitudinal and transverse measurements of the participants' heads, point CZ was located, followed by point FCZ at 40% along the longitudinal line from CZ, and point PZ at 70%. The neurofeedback intervention sessions took place over a 13-session training period, three times a week, with each session lasting 30 minutes (15 minutes of the beta increase/theta decrease protocol followed by 15 minutes of the alpha increase protocol) (Gordon et al., 2020) (Table 1). After the intervention, the post-test was administered in the same way as the pre-test.

One of the research tools used in this study is the N-Back test for improving working memory. In this test, the individual responds to a stimulus, such as a number, if it matches the one presented before it. The stimuli are presented continuously, and the individual's responses continue until all the stimuli have been shown.

Table 1. Neurofeedback Training Session Protocol (Beta Increase, Theta Decrease - Alpha Increase) (Part I)

Session	Brain region	Protocol	Therapeutic window	Brain region
1	Electrode attachment to point FCZ	Executing Protocol 1 (Beta Increase, Theta Decrease) for 15 minutes"	Basketball	Electrode attachment to point PZ
2			Puzzle	
3			Swing	
4			Galaxy	
5			Nature	
6			Star	
7			Mountains	
8			Historical sites	
9			Road	
10			Sky	
11			Rabbit	
12			Spaceship	
13			Basketball	

Table 1. Neurofeedback Training Session Protocol (Beta Increase, Theta Decrease - Alpha Increase) (Part II)

Session	Protocol	Therapeutic window	Threshold level	Start the counter
1	Executing Protocol 2 (Alpha Increase) for 15 minutes	Boat	80%	The number 4 gradually increased to 8 over time with success.
2		Boat	80%	
3		Boat	80%	
4		Boat	80%	
5		Boat	80%	
6		Boat	75%	
7		Boat	75%	
8		Boat	75%	
9		Boat	75%	
10		Boat	75%	
11		Boat	70%	
12		Boat	70%	
13		Boat	70%	

This test includes both visual and auditory sensory aspects, and memory score and reaction time are calculated separately for each sensory mode (Scharnowski et al., 2015). Bush et al. (2008) reported the reliability of this test using the test-retest method as 0.78, and Wayne Kirchner (1958) reported it as 0.9. Its validity was calculated using Cronbach's alpha method for internal consistency, resulting in 0.89 (Bush et al., 2008).

Another tool is the Wisconsin Card Sorting Test, used to assess cognitive flexibility. The computer version of this test has been used and validated in several studies (Deák & Wiseheart, 2015). Criterion validity in Anderson et al.'s (1991) study was reported as above 86% (Anderson, 1998), and its reliability was found to be 83% in Straus, E et al.'s (1991) study (Straus, Sherman, & Spreen, 2006). In the Iranian population, the test-retest reliability was reported as 85% (Ghadiri, Jazayeri, Ashaeri, & GHAZI, 2006).

The Iranian version of the Wisconsin test software was developed by Shaheghlian et al. (2011), where four main test cards (a red triangle, two green stars, three yellow plus signs, and four blue circles) are displayed at the top of the monitor screen, remaining visible until the test ends (Shahgholian, Azadfallah, Fathi Ashtiani, & Khoddadadi). Another 60 cards appear one by one in random order at the bottom of the screen near the right corner. When a card is displayed, the participant must decide under which main card the new card should be placed. Immediately after the participant's response, feedback appears on the screen in the form of "correct" or "incorrect."

The pattern for the four main cards is based on "color, shape, and number," and after six consecutive correct responses, the pattern changes; otherwise, the pattern remains the same. Therefore, the software uses the six correct responses as the basis for changing the pattern governing the main cards. The sequence of correct responses or received feedback is important. The software is designed to end the test and record the results once all 60 cards have been presented.

Two of these outputs, namely "Number of Categories Completed (Archieved)" and "number of perseverative errors," are considered the primary indicators for assessing executive functions (Dann et al., 2023). The third tool is the Continuous Performance Test (CPT), which was developed by Rosvold and colleagues in 1956 and quickly gained widespread acceptance. In the present study, the Conners Continuous Performance Test (CPT) was used to measure sustained attention. This test evaluates attentional errors or vigilance and impulsivity, is computer-based, and lasts 14 minutes (Folsom & Levin, 2021).

a b c

Figure 2. a. N-back test, b: Wisconsin card sorting test, c: Conner´s continue performance test

In this test, a series of English letters are presented at random intervals of 1, 2, or 4 seconds. All letters except for "X" are target stimuli, and the letter "X" serves as the non-target stimulus. The participant must press the space bar as quickly as possible upon seeing the target stimulus on the computer screen. In this test, two types of errors are scored: error of omission and error of commission. Additionally, the number of correct responses and the participant's reaction time to the stimuli are calculated.

The reliability coefficients for different parts of the test, administered 20 days apart to 43 elementary school boys, range from 0.59 to 0.93, with significant correlations at the 0.001 level. The test's validity was confirmed through criterion validation by comparing the performance of a normal group with a group with attention deficit/hyperactivity disorder (ADHD), showing significant differences between the two groups (Hadianfard, Najarian, Shokrkon, & Mehrabizadeh Honarmand, 2001).

The final tool is the neurofeedback device equipped with a computer system, which is used for neurofeedback training. In this tool, one electrode is placed on the head, and two electrodes are attached to the earlobes. Then, using computer equipment and based on the individual's brainwave patterns, visual and auditory feedback-usually in the form of a game, image, or sound-is presented to the individual. Through this method, the individual learns that they can control these feedbacks by using their brainwaves and creating different mental states. The continuation of this process leads to changes in brainwave patterns and improvement of their abnormalities (Enriquez-Geppert, Huster, & Herrmann, 2017). In the present study, the ProComp 2-channel neurofeedback device from Thought Technology Ltd. Canada was used.

Results

Initially, the Shapiro-Wilk test was used to determine the normality of data distribution, and Levene's test was employed to assess the homogeneity of variances. Subsequently, to examine the effect of the independent variable on the dependent variables, a mixed factorial analysis was conducted. For within-group changes, repeated measures analysis of variance (ANOVA) was used. To test each hypothesis, Mauchly's test was first applied to assess the sphericity assumption of the covariance matrix, and based on the results regarding sphericity, repeated measures ANOVA was performed. Finally, the LSD post-hoc test was used for pairwise comparisons of the test stages. The significance level for all inferential statistical methods was set at $P \leq 0.05$.

Figure 3. Neurofeedback training protocol (high beta, low theta and high alpha)

Table 2. Pairwise Comparisons for Post-Task Measures across Groups

Dependent variable	(I) group	(J) group	Mean difference (I-J)	SE	P-value[b]	95% CI for Difference[b]	
						Lower Bound	Upper Bound
postNback	Experience	Control	114.702	83.592	0.190	-63.469	292.873
	Control	Experience	-114.702	83.592	0.190	-292.873	63.469
postCPT	Experience	Control	4.564	21.077	0.831	-40.361	49.489
	Control	Experience	-4.564	21.077	0.831	-49.489	40.361
PostWisconsin	Experience	Control	-3.487*	1.109	0.007	-5.852	-1.122
	Control	Experience	3.487*	1.109	0.007	1.122	5.852

CI: Confidence Interval; SE: Standard error; CPT: Continuous Performance Test

*The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

In the overall hypothesis test, the results of the mixed factorial analysis (2*2) showed that, after eliminating the pre-test effect and based on Pillai's Trace, there was a significant difference between the experimental and control groups (F (1,18) = 6.135, P = 0.008, η^2p = 0.586). Additionally, the results of the LSD test showed that there was no significant difference between the experimental and control groups in working memory (P = 0.190) and sustained attention (P = 0.831), while a significant difference was observed in cognitive flexibility (P = 0.007) (Table 2).

The results of the repeated measures analysis of variance showed that, based on Pillai's Trace, there was no significant difference between the experimental and control groups in the working memory variable (response time and correct responses) (F (1,18) = 1.026, P = 0.324, η^2p = 0.054) (Table 3).

The results also showed that none of the main effects of group, training stages, or the interaction effect between group and training stages were significant (P > 0.05) (Table 4).

The results of the repeated measures analysis of variance showed that, based on Pillai's Trace, there was no significant difference between the experimental and control groups in the cognitive flexibility variable (number of categories and perseverative errors) (F (1,18) = 2.227, P = 0.149, η^2p = 0.112) (Table 5).

The results also indicated that none of the main effects of group, training stages, or the interaction effect between group and training stages were significant (P > 0.05) (Table 6).

The results of the repeated measures analysis of variance showed that, based on Pillai's Trace, there was no significant difference between the experimental and control groups in the sustained attention variable (correct responses and response time) (F (1,18) = 0.226, P = 0.640, η^2p = 0.012) (Table 7).

The results also showed that none of the main effects of group, training stages, or the interaction effect between group and training stages were significant (P > 0.05) (Table 8).

Discussion

The aim of the present study was to determine the effect of neurofeedback training on improving executive functions in middle school student-athletes.

Table 3. Multivariate Test Statistics for Nback Effect

Effect		Value	F	Hypothesis df	Error df	P-value	Partial Eta squared
Nback	Pillai's Trace	0.054	1.026	1.000	18.000	0.324	0.054
	Wilks' Lambda	0.946	1.026	1.000	18.000	0.324	0.054
	Hotelling's Trace	0.057	1.026	1.000	18.000	0.324	0.054
	Roy's Largest Root	0.057	1.026	1.000	18.000	0.324	0.054

df: Degree of freedom

Table 4. Tests of Within-Subjects Effects for Nback and Interaction with Group

Source		Type III sum of squares	df	Mean square	F	P-value	Partial Eta squared
Nback	Sphericity Assumed	31979.025	1	31979.025	1.026	0.324	0.054
	Greenhouse-Geisser	31979.025	1.000	31979.025	1.026	0.324	0.054
	Huynh-Feldt	31979.025	1.000	31979.025	1.026	0.324	0.054
	Lower-bound	31979.025	1.000	31979.025	1.026	0.324	0.054
Nback * group	Sphericity Assumed	3667.225	1	3667.225	0.118	0.736	0.006
	Greenhouse-Geisser	3667.225	1.000	3667.225	0.118	0.736	0.006
	Huynh-Feldt	3667.225	1.000	3667.225	0.118	0.736	0.006
	Lower-bound	3667.225	1.000	3667.225	0.118	0.736	0.006
Error (Nback)	Sphericity Assumed	560922.250	18	31162.347			
	Greenhouse-Geisser	560922.250	18.000	31162.347			
	Huynh-Feldt	560922.250	18.000	31162.347			
	Lower-bound	560922.250	18.000	31162.347			

df: Degree of freedom

The results of the 2x2 factorial analysis showed a significant difference between the experimental and control groups after removing the pre-test effect. According to the results of the LSD test, there was no significant difference between the experimental and control groups in the variables of working memory and sustained attention, while a significant difference was observed in cognitive flexibility. These findings align with the results of previous studies by Noshad and Azizi (2023) (Noshad & Azizi, 2023), Gordon et al. (2020) (Gordon et al., 2020), Cannon et al. (2009) (Cannon, Congedo, Lubar, & Hutchens, 2009), Xiong et al. (2014) (Xiong et al., 2014), and Lecomte and Juhel (2011) (Juhel, 2011), which concluded that the first hypothesis was rejected and neurofeedback did not improve working memory performance in healthy individuals. However, these findings are not consistent with the results of Nawaz et al. (2023) (Nawaz, Wood, Nisar, & Yap, 2023), Diamond (2020) (Schmidt et al., 2015, as cited in (Diamond, 2020), Chen and Sui (2023) (Chen & Sui, 2023), Matsuzaki et al. (2023) (Matsuzaki, Nouchi, Sakaki, Dinet, & Kawashima, 2023), Yang et al. (2023) (Yang et al., 2024), Dana et al. (2019) (Dana, Rafiee, & Gholami, 2019), Wang & Hsieh (2013), and Pei et al. (2018) (Pei et al., 2018).

These findings are also in line with the results of research by Nan et al. (2024) (Nan et al., 2024), Bagherzadeh et al. (2020) (Bagherzadeh, Baldauf, Pantazis, & Desimone, 2020), and Gonçavales et al. (2018) (Gonçalves, Carvalho, Mendes, Leite, & Boggio, 2018), which reject the second hypothesis, suggesting that neurofeedback has no effect on sustained attention in healthy individuals. However, they are inconsistent with the findings of Eftadeh Hal and Movahedi (2016) (Eftadeh Hal & Movahedi, 2016), Vernon et al. (2003) (Vernon et al., 2003), and Wang & Hsieh (2013) (Wang & Hsieh, 2013). Research shows that increased slow brainwaves in different regions are associated with poor impulse control and reduced attention and emotion regulation. Therefore, by decreasing or suppressing the amplitude of theta and delta waves, behavioral changes-especially in emotion and attention-can be observed in participants.

Table 5. Multivariate Test Statistics for Wisconsin Effect

Effect		Value	F	Hypothesis df	Error df	P-value	Partial Eta squared
Wisconsin	Pillai's Trace	0.112	2.277	1.000	18.000	0.149	0.112
	Wilks' Lambda	0.888	2.277	1.000	18.000	0.149	0.112
	Hotelling's Trace	0.126	2.277	1.000	18.000	0.149	0.112
	Roy's Largest Root	0.126	2.277	1.000	18.000	0.149	0.112

df: Degree of freedom

Table 6. Tests of Within-Subjects Effects for Wisconsin and Interaction with Group

Source		Type III sum of squares	df	Mean square	F	P-value	Partial Eta squared
Wisconsin	Sphericity Assumed	27.225	1	27.225	2.277	0.149	0.112
	Greenhouse-Geisser	27.225	1.000	27.225	2.277	0.149	0.112
	Huynh-Feldt	27.225	1.000	27.225	2.277	0.149	0.112
	Lower-bound	27.225	1.000	27.225	2.277	0.149	0.112
Wisconsin * group	Sphericity Assumed	9.025	1	9.025	0.755	0.396	0.040
	Greenhouse-Geisser	9.025	1.000	9.025	0.755	0.396	0.040
	Huynh-Feldt	9.025	1.000	9.025	0.755	0.396	0.040
	Lower-bound	9.025	1.000	9.025	0.755	0.396	0.040
Error (Wisconsin)	Sphericity Assumed	215.250	18	11.958			
	Greenhouse-Geisser	215.250	18.000	11.958			
	Huynh-Feldt	215.250	18.000	11.958			
	Lower-bound	215.250	18.000	11.958			

df: Degree of freedom

As a result, neurofeedback training can help adolescent athletes regulate brainwave activity and improve their working memory (Demos, 2005, cited in (Dana et al., 2019).

The mechanism of action for neurofeedback conditions the brain's electrical functions (Lubar, 2003), enabling the individual's performance to reach an optimal level (Kouijzer, van Schie, de Moor, Gerrits, & Buitelaar, 2010). Initially, these changes are short-term, but they gradually become more stable. Generally, healthier brainwave patterns can be relearned in most people with continued feedback, coaching, and practice (Hammond, 2007). Working memory and attention share common neural mechanisms, and they can be trained using top-down cognitive strategies (Gazzaley & Nobre, 2012). First, the link between attention and working memory shows a sequential relationship where attention is responsible for encoding and working memory is responsible for retaining information during task execution. (Attention acts as the gatekeeper of processing, and working memory serves as the bridge to performance) (Awh, Vogel, & Oh, 2006). Furthermore, these two systems rarely operate independently and may have relative dependencies on each other. According to the perceptual-load theory (Lavie, 1995), attention absorption is continuous, encoding both primary and delayed stimuli.

While the processing of relevant and irrelevant stimuli in working memory may require additional attention to succeed (Lavie, 1995), this process itself requires training. Studies have shown that brain activity patterns in skilled individuals differ from those of beginners, and recognizing the brainwave patterns of professional athletes before and during performance provides a rationale for creating or mimicking these patterns to improve the performance of non-professionals (Zadeh, 2019; Vernon, 2005, cited in). On the other hand, the human brain can repair itself, meaning it has the capacity to learn or relearn self-regulation of brainwaves (Demos, 2005, cited in (Dana et al., 2019).

Table 7. Multivariate Tests for Continuous Performance Test (CPT) Effect

Effect		Value	F	Hypothesis df	Error df	P-value	Partial Eta squared
Wisconsin	Pillai's Trace	0.012	0.226	1.000	18.000	0.640	0.012
	Wilks' Lambda	0.988	0.226	1.000	18.000	0.640	0.012
	Hotelling's Trace	0.013	0.226	1.000	18.000	0.640	0.012
	Roy's Largest Root	0.013	0.226	1.000	18.000	0.640	0.012

df: Degree of freedom

Table 8. Tests of Within-Subjects Effects for Continuous Performance Test (CPT) and Interaction with Group

Source		Type III sum of squares	df	Mean square	F	P-value	Partial Eta squared
CPT	Sphericity Assumed	409.600	1	409.600	0.226	0.640	0.012
	Greenhouse-Geisser	409.600	1.000	409.600	0.226	0.640	0.012
	Huynh-Feldt	409.600	1.000	409.600	0.226	0.640	0.012
	Lower-bound	409.600	1.000	409.600	0.226	0.640	0.012
CPT * group	Sphericity Assumed	129.600	1	129.600	0.072	0.792	0.004
	Greenhouse-Geisser	129.600	1.000	129.600	0.072	0.792	0.004
	Huynh-Feldt	129.600	1.000	129.600	0.072	0.792	0.004
	Lower-bound	129.600	1.000	129.600	0.072	0.792	0.004
Error (CPT)	Sphericity Assumed	32593.800	18	1810.767			
	Greenhouse-Geisser	32593.800	18.000	1810.767			
	Huynh-Feldt	32593.800	18.000	1810.767			
	Lower-bound	32593.800	18.000	1810.767			

df: Degree of freedom; CPT: Continuous Performance Test

In other words, neurofeedback is based on the principles of procedural skills learning (Ziabakhsh, Sharifi, Fath Abadi, & Nejati, 2020) and can regulate brain oscillations toward a homeostatic (balanced) point, achieved through top-down regulatory mechanisms (Ros, J. Baars, Lanius, & Vuilleumier, 2014). In explaining the effect of neurofeedback training on working memory and sustained attention, the importance of altering brainwave amplitudes (particularly 4-7 Hz and 15-18 Hz waves) in higher cognitive and brain functions must be highlighted. Research shows that increased slow brainwaves in various brain regions are associated with impulsivity and reduced attention and emotional regulation. Therefore, by decreasing or suppressing theta and delta wave amplitudes, behavioral changes, particularly in emotion and attention, can be observed in participants. As a result, neurofeedback training can help adolescent athletes regulate brainwave activity and improve their working memory. By providing feedback to the brain on the individual’s performance and the state of its bioelectric rhythms in the preceding seconds, neurofeedback encourages the brain to adjust, modify, and maintain the appropriate activity. In essence, the brain is asked to manipulate its various brainwaves by generating some waves while reducing others (Dana et al., 2019), a process that requires time for the brain to be trained, based on procedural skill learning (Ziabakhsh et al., 2020).

Additionally, the resource-control model and the opportunity-cost model suggest that intrinsic motivation during a particular task and the ability to exert influence diminish over time. The resource control model explains the decline in alertness over time as a tendency for attentional resource distraction, which is influenced by task difficulty and duration (Huang, Li, & Zhang, 2023). Generally, increasing task difficulty and duration demands greater use of available attentional resources, heightening the need for attention allocation (See et al., 1995, cited in Huang et al., 2023). Attentional resources are connected to the central executive attentional network (Gartenberg, Gunzelmann, Hassanzadeh-Behbaha, & Trafton, 2018).

The reduction of resources in the central executive network affects sustained attention and leads to errors in perception and information processing. Additionally, based on the "time on task performance" effect, executive control decreases as mind-wandering increases, gradually leading to more attentional resources being allocated to mind-wandering. From the perspective of alternative underload reduction, inattention and habituation to the target also result in a decrease in vigilance (Helton & Russell, 2012). Furthermore, neural oscillations in the alpha band are strongly associated with sustained attention, and alpha power increases during periods of mind-wandering compared to task-related cognitive phases. This suggests that the modulation of alpha activity may influence sustained attention (Nan et al., 2024). The findings of this study are consistent with the results of Hauser et al. (2015) (Hauser, Iannaccone, Walitza, Brandeis, & Brem, 2015), Kermani Mamazandi et al. (2017) (Mamazandi, Far, Pasand, Najafi, & Mahmoud, 2017), Zinke et al. (2012) (Zinke, Einert, Pfennig, & Kliegel, 2012), K Li et al. (2019) (Li et al., 2019), and Karbach et al. (2009) (Karbach & Kray, 2009), which support the third hypothesis and the positive impact of neurofeedback on cognitive flexibility in healthy individuals and athletes. However, these results are inconsistent with the findings of Navaz et al. (2022) (Nawaz, Nisar, Yap, & Tsai, 2022). Executive functions are a group of related higher-order cognitive processes responsible for cognitive flexibility and goal-directed behavioral adaptation (Friedman & Robbins, 2022).

Neurofeedback training goes beyond EEG and, through the use of fMRI (functional magnetic resonance imaging), fNIRS (functional near-infrared spectroscopy), and other methods for collecting neural signals, provides insight into the brain's functional dynamics. This comprehensive approach enables the targeted enhancement of cognitive flexibility and control—key elements in adapting strategies to varying conditions and organizing actions in alignment with goals. When highlighting the role of neurofeedback training in sports, it is crucial to underscore its contribution to increasing agility and mental focus. Such improvements are especially vital for athletes in precision-based disciplines (76), where athletic performance is intricately linked to cognitive abilities, particularly cognitive flexibility, alongside stress management and self-regulation. These sports require athletes to quickly adapt to changing conditions while maintaining focus under pressure. Cognitive flexibility allows athletes to effectively switch strategies, while self-regulation helps maintain focus and emotional balance (Corrado et al., 2024).

Cortical oscillations are used to understand the involvement of the cortex during the execution of different tasks. Initially, these changes are short-term, but they gradually become more sustained. It has also been observed that brainwave patterns can be retrained with continuous feedback to improve cognitive flexibility and control (Corrado et al., 2024). Cognitive flexibility enables learners to shift their focus between tasks, adjust their perspectives or problem-solving strategies, and adapt to new demands, rules, or priorities (Kolovelonis, Papastergiou, Samara, & Goudas, 2023). Among the components of executive functions, cognitive flexibility has a unique structure that distinguishes it from other key elements. From a psychometric perspective, there is a well-known issue in measuring components of executive functions, known as "task impurity." Most cognitive tasks involve non-executive functions and typically load differently on the three main components of executive functions (cognitive flexibility, working memory, and response inhibition). Almost all tasks carry a working memory load, and most include some degree of response inhibition. On one hand, there is a weak correlation between cognitive flexibility and IQ, whereas working memory shows a stronger correlation with IQ (the general factor) (Tong et al., 2023). On the other hand, individuals with higher emotional intelligence tend to have greater cognitive flexibility (Shiravi, Mottaqi, & Moradi Bidhendi, 2023). In other words, the ability to engage in goal-directed behavior and develop cognitive flexibility only emerges when a person understands that behaviors are mediated by internal states, and through proper control and interpretation of those states, one can adapt and become more flexible in external situations (Shirovi, Sh, & Moradi, 2020).

Conclusion

The study highlights that neurofeedback training can positively impact cognitive flexibility in student athletes, an essential aspect of executive functions. By targeting brainwave modulation (increasing beta waves, decreasing theta waves, and enhancing alpha waves), the neurofeedback sessions aimed to improve key executive functions like working memory, cognitive flexibility, and sustained attention. The results indicated a notable improvement in cognitive flexibility for the experimental group, though there were no significant differences between the experimental and control groups in working memory and sustained attention. This suggests that while neurofeedback can effectively enhance certain cognitive skills, its influence may vary across different components of executive functions.

In conclusion, neurofeedback shows promise in helping student athletes improve their adaptability to changing conditions and boosting their cognitive resilience. However, while the findings are encouraging, further research is necessary to comprehensively understand the specific effects and potential benefits of neurofeedback training in healthy individuals. Additional studies with larger sample sizes and varied athletic populations could provide deeper insights into how neurofeedback might be optimized for different aspects of mental performance in sports and beyond.

Conflict of Interests

Authors have no conflict of interests.

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