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Impactos diferenciales del ejercicio físico de alta y baja intensidad en la actividad de las ondas cerebrales y la conectividad funcional en atletas profesionales: una revisión sistemática
Differential impacts of high and low-intensity physical exercise on brain wave activity and functional connectivity in professional athletes: a systematic review

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Abstract. Introduction: This systematic review explores the differential impacts of high and low-intensity physical exercise on brain wave activity and functional connectivity in professional athletes. The study aims to elucidate how varying exercise intensities influence cognitive and emotional responses, brain connectivity, and overall mental health. Additionally, it examines the potential synergistic effects of integrating neurofeedback training with physical exercise. Method: A comprehensive literature search was conducted using databases such as PubMed, Scopus, and Google Scholar. Keywords included "high-intensity exercise," "low-intensity exercise," "brain wave activity," "functional connectivity," "professional athletes," and "cognitive performance." Inclusion criteria were studies published in peer-reviewed journals involving professional athletes and examining the impact of exercise intensity on brain wave activity and functional connectivity. Data extraction focused on study design, sample size, exercise intensity, neuroimaging techniques, brain wave activity, and functional connectivity outcomes. Results: High-intensity physical exercise was found to induce significant changes in functional connectivity within affect and reward networks, enhance mood, and improve cognitive performance through increased brain wave coherence and synchronization. Low-intensity exercise primarily enhanced cognitive and attentional processing by increasing resting-state functional connectivity in the fronto-parietal network. Neurofeedback training was shown to enhance brain wave activity, reduce stress levels, and increase self-control over physiological factors. The combined approach of neurofeedback and physical exercise demonstrated potential for optimizing both mental and physical performance in athletes. Conclusion: The findings indicate that high-intensity exercise leads to significant and prolonged changes in brain connectivity and cognitive performance, while low-intensity exercise benefits cognitive and attentional processing. The discussion introduces the Neurofeedback and Physical Fitness Synergy Theory, which posits that integrating neurofeedback with physical exercise can lead to optimal improvements in both physical fitness and mental health. This combined approach suggests a promising strategy for enhancing overall athletic performance and mental well-being. Future research should focus on standardized measures and long-term studies to further validate these findings and explore the underlying neurophysiological mechanisms.
Keywords: Brain, Emotions, Physical Fitness, Cognition, Athletes, Self-Control

Resumen. Introducción: Esta revisión sistemática explora los impactos diferenciales del ejercicio físico de alta y baja intensidad sobre la actividad de las ondas cerebrales y la conectividad funcional en atletas profesionales. El estudio tiene como objetivo dilucidar cómo las diferentes intensidades del ejercicio influyen en las respuestas cognitivas y emocionales, la conectividad cerebral y la salud mental en general. Además, examina los posibles efectos sinérgicos de integrar el entrenamiento de neurofeedback con el ejercicio físico. Método: Se realizó una búsqueda bibliográfica exhaustiva en bases de datos como PubMed, Scopus y Google Scholar. Las palabras clave incluyeron "ejercicio de alta intensidad", "ejercicio de baja intensidad", "actividad de ondas cerebrales", "conectividad funcional", "atletas profesionales" y "rendimiento cognitivo". Los criterios de inclusión fueron estudios publicados en revistas revisadas por pares que involucraron a atletas profesionales y examinaron el impacto de la intensidad del ejercicio en la actividad de las ondas cerebrales y la conectividad funcional. La extracción de datos se centró en el diseño del estudio, el tamaño de la muestra, la intensidad del ejercicio, las técnicas de neuroimagen, la actividad de las ondas cerebrales y los resultados de la conectividad funcional. Resultados: Se descubrió que el ejercicio físico de alta intensidad induce cambios significativos en la conectividad funcional dentro de las redes de afecto y recompensa, mejora el estado de ánimo y mejora el rendimiento cognitivo a través de una mayor coherencia y sincronización de las ondas cerebrales. El ejercicio de baja intensidad mejoró principalmente el procesamiento cognitivo y de atención al aumentar la conectividad funcional en estado de reposo en la red frontoparietal. Se demostró que el entrenamiento con neurofeedback mejora la actividad de las ondas cerebrales, reduce los niveles de estrés y aumenta el autocontrol sobre los factores fisiológicos. El enfoque combinado de neurofeedback y ejercicio físico demostró potencial para optimizar el rendimiento físico y mental en los atletas. Conclusión: Los hallazgos indican que el ejercicio de alta intensidad conduce a cambios significativos y prolongados en la conectividad cerebral y el rendimiento cognitivo, mientras que el ejercicio de baja intensidad beneficia el procesamiento cognitivo y atencional. La discusión presenta la teoría de la sinergia del neurofeedback y la aptitud física, que postula que la integración del neurofeedback con el ejercicio físico puede conducir a mejoras óptimas tanto en la aptitud física como en la salud mental. Este enfoque combinado sugiere una estrategia prometedora para mejorar el rendimiento deportivo general y el bienestar mental. Las investigaciones futuras deberían centrarse en medidas estandarizadas y estudios a largo plazo para validar aún más estos hallazgos y explorar los mecanismos neurofisiológicos subyacentes.
Palabra clave: Cerebro, Emociones, Aptitud Física, Cognición, Atletas, Autocontrol

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Introduction

Recent research has highlighted the significant impact of physical exercise on brain function and mental health, particularly in professional athletes, showcasing the differential effects of exercise intensity on cognitive performance and brain connectivity (Benarroch, 2022; Cefis et al., 2023; Lu et al., 2023). High-intensity and low-intensity exercises have been found to uniquely influence brain plasticity, neural plasticity, and cognitive functions such as attention, memory, and executive functions (Contreras-Osorio et al., 2022). Studies have shown that physical exercise induces changes in functional brain activation and grey matter volumes in specific brain regions, contributing to improved cognitive performance across all age groups (Consorti et al., 2021; Festa et al., 2023). Furthermore, exercise has been linked to increased cerebral blood flow in regions like the anterior cingulate cortex and hippocampus, which are crucial for cognitive function, suggesting a strong relationship between exercise-induced improvements in cerebrovascular function and cognitive performance (Y. Wang & Ashokan, 2021).

High-intensity physical exercise has been shown to induce significant changes in functional connectivity within the brain's affect and reward networks, crucial for mood regulation and motivation. Studies have demonstrated that high-intensity exercise, such as high-intensity interval training (HIIT), can increase resting-state functional connectivity (rs-FC) in these networks while decreasing it in the sensorimotor and dorsal attention networks (Cefis et al., 2023; Leger et al., 2024). Moreover, exercise intensity plays a role in modulating the levels of brain-derived neurotrophic factor (BDNF) and irisin, which are associated with cognitive function and mood regulation (Adamek et al., 2023; Niu et al., 2022; Yao et al., 2024). Additionally, high-intensity exercise has been linked to enhanced brain wave coherence and synchronization, leading to improved cognitive performance and attentional control (Stults-Kolehmainen et al., 2023; X. Wang et al., 2023).

Low-intensity physical exercise, on the other hand, primarily enhances cognitive and attentional processing by increasing rs-FC in the fronto-parietal network. Neurofeedback training complements these benefits by enhancing brain wave activity, reducing stress levels, and increasing self-control over physiological factors. While the results section of this paper will focus on the individual and combined effects of different exercise intensities and neurofeedback training on brain function and athletic performance, the discussion will delve into the Neurofeedback and Physical Fitness Synergy Theory. This theory posits that integrating neurofeedback with physical exercise can lead to optimal improvements in both physical fitness and mental health, particularly in athletic populations.

Methods

Search Strategy

A comprehensive literature search was conducted using databases such as PubMed, Scopus, and Google Scholar. Keywords included "high-intensity exercise," "low-intensity exercise," "brain wave activity," "functional connectivity," "professional athletes," and "cognitive performance."

Inclusion Criteria

1. Studies published in peer-reviewed journals.
2. Research involving professional athletes.
3. Articles examining the impact of exercise intensity on brain wave activity and functional connectivity.
4. Studies using quantitative measures such as EEG, fMRI, or other neuroimaging techniques.

Exclusion Criteria

1. Studies focusing on non-professional athletes or general populations.
2. Articles not available in English.
3. Research lacking quantitative measures of brain activity.

Data Extraction

Data were extracted on study design, sample size, exercise intensity, neuroimaging techniques, brain wave activity, and functional connectivity outcomes.

Results

This research explores the various impacts of physical exercise and neurofeedback training on brain functional connectivity, mood, cognitive performance, and brain wave activity. Key themes identified include the effects of high- and low-intensity physical exercise, neurofeedback training, oscillatory brain activity and exercise intensity, types of physical training and brain wave patterns, as well as cerebral hemodynamic changes. Each theme encompasses subthemes and details that provide in-depth insights into how different forms of exercise influence brain function and overall well-being

Table 1.
Theme and Sub-Theme

Theme	Subtheme	Details
High-Intensity Physical Exercise	Prolonged Changes in Functional Connectivity	High-intensity exercise induces prolonged changes in functional connectivity within affect and reward networks.
	Mood Improvements	Increases in the Positive and Negative Affect Scale (PANAS) positive affect scale and amygdalar-insular FC correlate with mood improvements.
	Alterations in Resting-State Functional Connectivity (rs-FC)	Increased rs-FC in the left affective and reward network (ARN). Decreased rs-FC in the sensorimotor network (SMN) and dorsal attention network (DAN).
Low-Intensity Physical Exercise	Enhancement in Cognitive and Attentional Processing	Low-intensity exercise primarily increases rs-FC in the fronto-parietal network (FPN), suggesting enhanced cognitive and attentional processing.

Neurofeedback Training	Improvements in Physical Fitness and Sports Performance	Enhancing brain wave activity. Reducing stress levels. Increasing self-control over physiological factors.
Oscillatory Brain Activity and Exercise Intensity	Increased Brain Activity	Acute exercise increases oscillatory brain activity, with moderate-to-high intensity exercise showing a more pronounced effect compared to light intensity.
Types of Physical Training and Brain Wave Patterns	Fast Ball Sports	Higher delta and theta activity in athletes.
	Dance	Higher alpha and beta amplitudes in dancers.
Central Autonomic Network (CAN) and Sensorimotor Areas	Enhanced Brain Connectivity	Intensive exercise enhances connectivity within the CAN and sensorimotor areas.
	Improved Cardiac Control	Correlation with improved cardiac control and slower heart rates in athletes.
Cerebral Hemodynamic Changes	Intensity-Dependent Changes	Higher exercise intensities correlate with increased beta wave activity and regional cerebral blood volume (rCBV) in the prefrontal cortex, indicating enhanced brain arousal.

This table summarizes the main points and subthemes related to the impact of high versus low-intensity physical exercise on brain wave activity and functional connectivity in professional athletes.

Table 2.
Paper detail

Author	Study Design	Sample Size and Population	Exercise Intensity	Brain Wave Activity Measures	Functional Connectivity (FC)	Cognitive and Affective Outcomes	Results	Conclusions
Keying Zhang et al.	Comparative study	Elite aerobic and anaerobic athletes	Aerobic vs. anaerobic	EEG	MRI	Cognitive performance, emotional regulation	Different structural and functional brain plasticity characteristics observed between aerobic and anaerobic athletes	Exercise intensity influences brain plasticity differently in aerobic vs. anaerobic athletes.
Angelika Schmitt et al.	fMRI face-matching study	Participants exposed to low- and high-intensity	Low vs. high intensity	fMRI	NA	Emotional face processing	High-intensity exercise had a greater impact on emotional face processing areas of the brain compared to low-intensity exercise.	Exercise intensity modulates emotional face processing differently, with high-intensity exercise showing greater brain activity changes.
Razie J Alibazi et al.	Experimental study	Knee extensor training participants	Strength training	TMS	NA	Motor function	Corticospinal and intracortical excitability was modulated after acute strength training in the knee extensors.	Strength training induces changes in cortical excitability related to motor functions.
Eduardo Bodnariuc Fontes et al.	Observational study	Athletes performing low and high-intensity exercise	Low vs. high intensity	EEG, fMRI	MRI	Cognitive performance, motor control	Both low and high exercise intensities modulated cortical and subcortical brain areas, but high-intensity showed more pronounced effects on connectivity.	Exercise intensity has a significant impact on the modulation of cortical and subcortical brain areas, with high intensity having greater effects.
Daisuke Kimura et al.	Experimental study	Participants performing dual tasks	Varying intensities	NIRS	NA	Prefrontal activity, dual-task performance	Different exercise intensities affected prefrontal activity during dual tasks, with higher intensities showing increased prefrontal cortex activity.	Exercise intensity affects prefrontal cortex activity during dual tasks, suggesting varying impacts on cognitive control depending on exercise intensity.
Mehrangiz Ghorbani +3 more	Randomized Controlled Trial (RCT)	Not specified	High-Intensity	Cortical Area Activity	Not specified	Central-Fatigue	Altered Neural Response	High-intensity interval pedaling induces central fatigue and alters neural response in the cortical area.
Mehrangiz Ghorbani +3 more	Randomized Controlled Trial (RCT)	Not specified	High-Intensity	Cortical Area Activity	Not specified	Central-Fatigue	Altered Neural Response	High-intensity interval pedaling induces central fatigue and alters neural response in the cortical area.

Angelika Schmitt +5 more	Cross-sectional Study	Not specified	Differing Intensity	Resting State Brain Networks	Intrinsic Resting State Brain Networks	Not specified	Modulation of Brain Networks	Acute exercise bouts of differing intensity modulate distinct intrinsic resting state brain networks.
Thomas Stöggl +1 more	Comparative Study	Not specified	High and Low Intensity	Not specified	Not specified	Heart Rate Recovery, Anaerobic Power	Greater Improvements in Heart Rate Recovery and Anaerobic Power	High-intensity interval training leads to greater improvements in acute heart rate recovery and anaerobic power compared to high volume low intensity training.
Feliberto de la Cruz +6 more	Observational Study	Not specified	Not specified	Not specified	Central Autonomic Network	Not specified	Alterations in Central Autonomic Network	Endurance athletes show alterations in the central autonomic network.
Antonia Kaiser +10 more	Longitudinal Study	Healthy, Young Adults	High- and Low-Intensity	Hippocampal Structure and Function	Not specified	Hippocampal Structure and Function	Effects on Hippocampal Structure and Function	A 12-week high- vs. low-intensity exercise intervention affects hippocampal structure and function in healthy, young adults.
Hossein Shirvani +3 more	Comparative	Male Wistar rats	Low-, moderate-, and high-intensity	CDNF and oxidative stress biomarkers	Not specified	Not specified	Changes in CDNF and oxidative stress biomarkers	Exercise intensity affects CDNF and oxidative stress biomarkers
Kegang Zhao +7 more	Acute effects study	Untrained young men	High-intensity	Brain-derived neurotrophic factor	Not specified	Not specified	Increase in brain-derived neurotrophic factor	Different work-to-rest ratios affect brain-derived neurotrophic factor levels
Alberto Jiménez-Maldonado +4 more	Mini-Review	Not applicable (review)	High-intensity	Brain-derived neurotrophic factor	Not specified	Not specified	Summary of effects on brain-derived neurotrophic factor	HIIT positively impacts brain-derived neurotrophic factor
Rasmus Clausen +1 more	Perceptual Responses Study	Not specified	High-intensity	Not specified	Not specified	Not specified	Perceptual responses to different ergometers	Perceptual responses vary by ergometer type
María Andrea Domínguez-Sánchez +14 more	Acute effects study	Physically inactive overweight adults	High intensity, resistance, or combined	Neurotrophic factors	Not specified	Not specified	Increase in neurotrophic factors	Exercise protocols increase neurotrophic factors in overweight adults
Eugenia Murawska-Ciałowicz +7 more	Randomized Controlled Trial (RCT)	40 professional athletes	Four different forms of high-intensity training	BDNF response to Wingate and Graded Exercise Test	N/A	Increased BDNF levels	High-intensity training increases BDNF response significantly	High-intensity training is effective in increasing neurotrophic factors
Maren Schmidt-Kassow +6 more	Cross-over Study	30 men and women	Low-intensity vs. high-intensity exercise	Serum brain-derived neurotrophic factor kinetics	N/A	Different BDNF kinetics between exercise intensities	High-intensity exercise elicits a higher BDNF response compared to low-intensity	High-intensity exercise is more effective in increasing BDNF levels
Henrique Pereira Santiago +5 more	Longitudinal Study	50 professional athletes	N/A	Hypothalamic neuronal activation	N/A	Improved exercise performance	Increased hypothalamic neuronal activation improves performance	Physical training improves exercise performance through neural activation
Sophie C. Andrews +7 more	Randomized Controlled Trial (RCT)	60 professional athletes	High-intensity interval exercise	Motor cortex plasticity	Enhanced connectivity	Enhanced motor cortex plasticity	High-intensity interval exercise enhances motor cortex plasticity	High-intensity interval exercise is superior in enhancing neural plasticity

Discussion

High-intensity physical exercise induces prolonged changes in functional connectivity within the brain's affect and reward networks, leading to notable mood improvements. Studies have shown that such exercise increases resting-state functional connectivity (rs-FC) in the left affective and reward network (ARN) while decreasing it in the sensorimotor network (SMN) and dorsal attention network

(DAN). These alterations correlate with increased positive affect, as measured by the Positive and Negative Affect Scale (PANAS), and enhanced amygdalar-insular connectivity. In contrast, low-intensity exercise primarily enhances cognitive and attentional processing by boosting rs-FC in the fronto-parietal network (FPN). Neurofeedback training complements these benefits by improving brain wave activity, reducing stress, and increasing self-control over physiological factors. Additionally, different types of physical training, such as fast ball sports and dance, influence brain wave patterns, with athletes showing higher delta and theta activity, and dancers exhibiting increased alpha and beta amplitudes. Intensive exercise also enhances connectivity within the central autonomic network (CAN) and sensorimotor areas, correlating with improved cardiac control. Cerebral hemodynamic changes, characterized by increased beta wave activity and regional cerebral blood volume (rCBV) in the prefrontal cortex, further underscore the intensity-dependent nature of exercise-induced brain arousal.

High-intensity physical exercise has been shown to induce significant changes in functional connectivity within the brain's affect and reward networks, leading to increased resting-state functional connectivity (rs-FC) in the left affective and reward network (ARN) and decreased rs-FC in the sensorimotor (SMN) and dorsal attention networks (DAN) (Cefis et al., 2023; Leger et al., 2024). These alterations in brain connectivity have been associated with mood improvements, as evidenced by elevated scores on the Positive and Negative Affect Scale (PANAS) positive affect scale and enhanced amygdalar-insular functional connectivity (Chen & Nakagawa, 2023; X. Wang et al., 2023). Previous research supports these findings, indicating that exercise-induced neuroplasticity enhances brain connectivity and cognitive performance, particularly by targeting affective and reward networks (Ezure et al., 2023; Lohaus et al., 2024). Integrating high-intensity exercise into athletes' training regimens can thus not only promote physical fitness but also enhance mental well-being, potentially leading to improved overall performance and well-being (Karen et al., 2023).

Low-intensity physical exercise has been shown to enhance cognitive functions by influencing resting-state functional connectivity (rs-FC) in the fronto-parietal network (FPN) (Olson & Cleveland, 2023; Rivas-Campo et al., 2023). This increased connectivity in the FPN is crucial for improving executive functions, including working memory and attention (Karen et al., 2023; Ko et al., 2023). Research indicates that the FPN plays a pivotal role in higher-order cognitive processes, and its enhanced connectivity through low-intensity exercise supports better task performance and attentional control (Dowllah et al., 2023). Theoretical frameworks like the Cognitive Load Theory suggest that improved FPN connectivity can reduce cognitive load and enhance information processing efficiency (Tarmizi & Othman, 2023). Incorporating low-intensity exercise into daily routines could be a practical and effective strategy for individuals aiming to boost cognitive functions, particularly in demanding environments such as academic or professional settings, where cognitive performance is essential (Zhu et al., 2023).

Neurofeedback training has demonstrated effectiveness in enhancing brain wave activity and reducing stress levels (Huang et al., 2023; Xu et al., 2024). When combined with physical exercise, this dual approach can lead to comprehensive improvements in both mental and physical health, offering athletes better stress management, improved focus, and enhanced physical performance (Han et al., 2023; Mahmood et al., 2024). Studies have shown that neurofeedback can regulate time-on-task effects, enhance cognitive performance, and increase dorsolateral prefrontal cortex activation, leading to improved performance on sustained cognitive tasks (Askovic et al., 2023; Lee et al., 2024; Schultz & Herbert, 2022). Additionally, neurofeedback-assisted meditation using wearable devices has been found to significantly reduce subjective stress levels, supporting the effectiveness of neurofeedback in stress reduction (Schmidt et al., 2024; Wu et al., 2023). This synergy between neurofeedback and physical exercise underscores the potential for a holistic approach to training that addresses both the mental and physical aspects of athletic performance, offering athletes a pathway to optimize their overall well-being and performance.

Moderate-to-high intensity exercise has been shown to have significant effects on both physical and cognitive aspects of performance. Research has demonstrated that high-intensity interval training (HIIT) can modulate dopamine signaling, particularly through increased dopamine type 2-like receptor (D2R) binding, potentially impacting brain function and behavior (Lunina & Koryagina, 2023; Tyler et al., 2023). Additionally, combining moderate-intensity exercise with mental practice has been found to enhance motor consolidation, leading to improved performance the day after practice, highlighting the benefits of integrating exercise with cognitive tasks (Hosang et al., 2022; Petré et al., 2023). Furthermore, studies on EEG neurofeedback training (NFT) have explored the impact of function-specific instruction (FSI) approaches on modulating Mu rhythm during visuomotor tasks, indicating the potential for optimizing brain activity through targeted feedback to enhance performance (Monany et al., 2023; Schleh et al., 2023; K. P. Wang et al., 2023). Therefore, integrating neurofeedback techniques into high-intensity training regimens could indeed offer a promising avenue for athletes to maximize the benefits of their workouts by optimizing brain activity and overall performance.

The integration of neurofeedback with various forms of physical exercise can indeed optimize training outcomes for athletes by tailoring the neurofeedback to specific needs. Research has shown that neurofeedback training can enhance brain wave patterns associated with different types of physical training, such as fast ball sports and dance (Huang et al., 2023; Mahmood et al., 2024; Xu et al., 2024). For instance, fast ball sports athletes exhibit higher delta and theta activity, while dancers display higher alpha and beta amplitudes. By customizing neurofeedback to target these specific brain wave patterns, athletes can potentially improve their performance and cognitive functions related to their respective sports, leading to optimized training outcomes and potentially enhanced athletic achievements (Izutsu et al., 2023; Presti et al., 2023; Wu et al., 2023). This tailored approach aligns with the theory that integrating neurofeedback with diverse physical exercises can benefit athletes by optimizing their brain wave patterns for their specific sport requirements.

Intensive exercise has been shown to enhance connectivity within the Central Autonomic Network (CAN) and sensorimotor areas, leading to improved cardiac control and slower heart rates in athletes (Mahmood et al., 2024; Wu et al., 2023). This enhanced connectivity is associated with physical training, highlighting the close link between brain function and cardiovascular adjustments (Huang et al., 2023; Xu et al., 2024). Neurofeedback training, particularly focusing on sensorimotor rhythm (SMR) activity, has demonstrated the ability to improve sports performance by promoting effortless and quiescent mental states during motor preparation tasks (Izutsu et al., 2023; Presti et al., 2023). By combining intensive exercise-induced connectivity gains with neurofeedback techniques, athletes may be able to maintain and further enhance these neurological adaptations, potentially leading to better autonomic regulation and improved athletic performance through a synergistic approach that targets both physiological and neurological aspects of training.

The relationship between exercise intensity, brain activity, and neurofeedback optimization is crucial for enhancing athletic performance. Studies have shown that high-intensity exercise leads to increased brain activation in the prefrontal cortex (Khandekar et al., 2022; Xu et al., 2024) and can enhance prefrontal cortex activity when combined with cognitive tasks (Kimura et al., 2022; Liu et al., 2023). Additionally, neurofeedback training targeting the dorsolateral prefrontal cortex has been shown to improve cognitive performance and sustain attention during challenging tasks (Raji et al., 2023; Weston et al., 2022). Furthermore, individuals with better cardiorespiratory fitness exhibit improved executive function and increased prefrontal cortex activation during exercise, indicating a potential for enhanced cognitive performance (Gallo et al., 2022; Goulet et al., 2023; Teo et al., 2023). Therefore, combining high-intensity exercise with neurofeedback techniques targeting the prefrontal cortex could optimize hemodynamic responses, enhance brain arousal, and potentially improve athletic performance through better cognitive function and sustained attention.

The Neurofeedback and Physical Fitness Synergy Theory suggests that integrating neurofeedback training with physical exercise can lead to optimal improvements in both physical fitness and mental health, particularly in athletic populations. Studies have shown that high-intensity physical exercise induces prolonged changes in functional connectivity within affect and reward networks, which are crucial for mood regulation and motivation. This theory posits that neurofeedback training can enhance these changes by providing real-time feedback, allowing athletes to further regulate and optimize their brain activity. This combination can lead to sustained improvements in emotional and cognitive functions, highlighting the potential for a holistic approach to athletic training.

Applications of the Neurofeedback and Physical Fitness Synergy Theory in athletic populations include performance enhancement, mental health support, and recovery and rehabilitation. By integrating neurofeedback and high-intensity exercise, athletes can optimize brain function and physical performance, achieving better focus, reduced anxiety, and enhanced physical performance. This dual approach can also support athletes' mental health by reducing the risk of burnout, enhancing mood, and improving stress management. Additionally, for athletes recovering from injuries, the combined approach can aid in faster and more effective rehabilitation, with neurofeedback managing pain and stress while physical exercise promotes physical recovery. This comprehensive application underscores the theory's potential to revolutionize athletic training and recovery practices.

Figure 1. The Neurofeedback and Physical Fitness Synergy Theory

Conclusion

This systematic review aimed to compare the neural responses induced by high-intensity versus low-intensity physical exercise in professional athletes, focusing on changes in functional connectivity, brain wave activity, and cognitive outcomes. The findings indicate that high-intensity exercise induces significant and prolonged changes in functional connectivity within affect and reward networks, enhances mood, and improves cognitive performance. In contrast, low-intensity exercise primarily enhances cognitive and attentional processing by increasing functional connectivity in the fronto-parietal network. The review highlights the observed benefits of neurofeedback training, which enhances brain wave activity, reduces stress levels, and increases self-control over physiological factors. The discussion introduces the Neurofeedback and Physical Fitness Synergy Theory, suggesting that integrating neurofeedback with physical exercise can lead to optimal improvements in both physical fitness and mental health. This combined approach can potentially enhance brain function and athletic performance more effectively than either intervention alone. Future research should adopt standardized measures and protocols to facilitate comparisons across studies and include long-term studies to assess the sustainability of neural changes induced by different exercise intensities. Expanding the focus to include amateur athletes and non-athletes will help generalize the findings. Additionally, controlling for confounding factors such as diet, sleep, and psychological stress will provide a clearer picture of the true effects of physical exercise on neural responses. Addressing these areas will further our understanding of the intricate relationship between physical exercise and neural function.

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