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Effects of real-time EEG neurofeedback training on cognitive, mental, and motor performance in elite athletes: a systematic review and meta-analysis

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Abstract

Study aim: Real-time EEG neurofeedback (NFB) training is gaining popularity as a cognitive-motor enhancement tool in elite sports. However, its protocol-specific effectiveness across disciplines and outcome domains remains unclear. This systematic review and meta-analysis examined the effects of real-time EEG NFB in elite athletes, focusing on protocol characteristics, targeted outcomes, and effect sizes.
Material and methods: A search of six databases (2000–2025) identified 24 studies involving national- or international-level athletes. Protocols were categorized by frequency band (e.g., SMR, beta, theta), sport discipline, and performance domain (cognitive, motor, psychological). Risk of bias was assessed using RoB 2 and ROBINS-I; GRADE was applied to evaluate evidence certainty. Eleven studies provided quantitative data for meta-analysis using standardized mean differences (SMD).
Results: Most studies involved individual sports, with judo, archery, and shooting most common. SMR and beta protocols dominated in precision sports; theta protocols were prevalent in combat sports. Meta-analysis showed a large pooled effect (SMD = 1.26; 95% CI: 1.05–1.45), with high heterogeneity (I^2 = 94.1%). GRADE indicated moderate certainty for cognitive and psychological outcomes.
Conclusion: EEG NFB appears effective in enhancing attention, motor control, and anxiety regulation in elite athletes. However, methodological variability highlights the need for standardized protocols and further replication.

Keywords: Cognitive enhancement – Psychomotor regulation – Attentional control – Performance optimization – Brain-computer interface

Introduction

In high-performance sport, marginal gains in attention, decision-making, and motor control can profoundly influence competitive success. Recent advancements in sport neuroscience have introduced real-time electroencephalographic (EEG) neurofeedback as a promising intervention to optimize performance-relevant brain activity. EEG neurofeedback enables athletes to self-regulate specific frequency bands—such as SMR (12–15 Hz), beta (13–30 Hz), and theta (4–8 Hz)—each associated with distinct neurophysiological functions. SMR protocols aim to enhance sensorimotor inhibition and postural stability by increasing activity over central sensorimotor areas (usually Cz), facilitating relaxed alertness and reduced motor excitability. Beta protocols are linked to active concentration, attentional focus, and cognitive control, particularly involving frontal and central regions. In contrast, theta training—often in the context of theta/beta ratios—targets deeper attentional states, working memory, and internalized focus, typically modulating midline frontal areas. These mechanisms are considered especially relevant for optimizing performance in high-cognitive or psychomotor-demand sports (Gruzelier, 2013; Gong et al., 2021; Hammond, 2007;

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Zoefel et al., 2011; Escolano et al., 2014). Recent systematic and narrative reviews (Tosti et al., 2024; Diotaiuti et al., 2024a; Diotaiuti et al., 2024b) have highlighted the efficacy of neurofeedback approaches in both performance regulation and clinical or cognitive contexts, emphasizing the growing importance of protocol personalization and integration with biofeedback techniques.

The mechanisms underlying EEG neurofeedback rely on operant conditioning, wherein athletes receive real-time feedback on their brain activity and adjust it toward targeted states. This approach has been associated with enhancements in focus, emotional regulation, reaction speed, and sensorimotor integration, making it especially relevant in sports requiring high cognitive and psychomotor demands (Da Silva & De Souza 2021; Gołaś et al., 2024). These demands are particularly pronounced in disciplines involving coordinated segmental movement and postural control, such as sport dance or precision sports (Kuliś & Gajewski, 2022).

Previous studies across sport disciplines, particularly in precision sports such as archery, shooting, and golf, report that beta and sensorimotor rhythm (SMR) protocols enhance attentional focus and reduce competition anxiety (Landers et al., 1991; Cheng et al., 2015; van Boxtel et al., 2024). In contrast, theta/beta protocols are frequently used in combat and power sports, aiming to improve complex motor control, balance, and visual reaction times (Maszczyk et al., 2020; Prończuk et al., 2023a). Despite these findings, heterogeneity in protocol parameters—such as session duration (ranging from 4 to 45 minutes), number and frequency of sessions, targeted EEG frequency bands (e.g., SMR vs. theta/beta), and type of feedback provided (visual, auditory, or combined)—as well as in study designs and outcome assessments, limits cross-study comparability.

Furthermore, the literature remains skewed toward individual sports, with few studies addressing team-based or open-skill contexts (van Boxtel et al., 2024). Given that team sports involve unique demands such as interpersonal coordination, tactical adaptation, and rapid decision-making under pressure, future research should explore how neurofeedback protocols can be tailored to enhance collective performance and cognitive functioning in team-based environments. Although immediate post-intervention effects appear consistently positive, particularly in domains such as attention and anxiety, evidence regarding long-term or transferable benefits remains limited (Toolis et al., 2023; Skalski et al., 2024). Additionally, the impact of environmental moderators (training frequency, hypoxia) and individual athlete characteristics is rarely addressed systematically. To address these gaps, the present work offers a systematic review and meta-analysis of studies evaluating the effects of real-time EEG neurofeedback training on cognitive, mental, and motor performance in elite athletes.

This review aims to systematically summarize and categorize existing empirical evidence on real-time EEG neurofeedback training in elite athletes, with particular emphasis on how outcomes vary by protocol type, sport discipline, and performance domain. Furthermore, it seeks to quantify the magnitude of intervention effects, where data allow, through meta-analytic techniques. Finally, this review intends to critically appraise the methodological quality of included studies and identify key limitations in the current literature, thereby offering clear recommendations for future research and practical implementation in high-performance sport contexts.

Material and methods

Protocol and registration

This systematic review and meta-analysis was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The review protocol was prospectively registered in the PROSPERO database under the title "Real-Time EEG Neurofeedback and Athletic Performance: A Systematic Review of Cognitive and Motor Outcomes in Elite Sport" (registration number: CRD4201020923).

Eligibility criteria

Studies were included if they met the following criteria:

- Population: elite or high-performance athletes competing at national or international levels;
- Intervention: real-time EEG-based neurofeedback targeting specific frequency bands (SMR, beta, alpha, theta);
- Comparator: control group, sham neurofeedback, or pre-post comparison;
- Outcomes: at least one performance-related outcome, including cognitive (attention, decision-making), motor (reaction time, coordination), or psychological (anxiety, imagery);
- Study design: randomized controlled trials, quasi-experimental studies, or controlled before-and-after trials;
- Language: English or Spanish;
- Other: minimum 3 sessions of neurofeedback and a sample size of ≥ 5 participants.

Studies were excluded if they:

(a) focused solely on clinical or rehabilitation populations (e.g., ADHD, stroke);
(b) did not use real-time feedback (e.g., post-session or offline neuroimaging analysis);
(c) employed non-EEG-based feedback modalities such as fMRI, near-infrared spectroscopy (NIRS), or heart rate variability (HRV). These methods were excluded due to their fundamentally different neurophysiological targets, lack of millisecond-level temporal resolution, and limited suitability for dynamic sport-specific training;

(d) involved fewer than three neurofeedback sessions;
(e) lacked a performance-related outcome; or
(f) had insufficient methodological detail for quality assessment.

Information sources and search strategy

We performed comprehensive searches in the following databases: PubMed, Scopus, Web of Science, SPORTDiscus, and EMBASE (2000–March 2025). The search strategy combined free-text terms and controlled vocabulary where available. Keywords included variations and Boolean combinations such as:

("neurofeedback" OR "neurofeedback training") AND ("EEG" OR "electroencephalography") AND ("elite athlete" OR "high-performance athlete") AND ("cognitive" OR "motor" OR "performance").

No restrictions were placed on the specific sporting discipline or neurofeedback protocol during the initial search phase. The search was limited to studies published in English or Spanish and involving human participants. Reference lists of eligible articles were also manually screened to identify additional studies.

The search strategy was designed to ensure maximal sensitivity in identifying studies suitable for both qualitative synthesis and quantitative meta-analysis.

Study selection and screening

The initial database search yielded a total of 497 records. After the removal of duplicate records ($n = 110$), studies excluded by automation tools ($n = 177$), and records removed for other reasons ($n = 20$), a total of 190 titles and abstracts were screened for potential eligibility. Figure 1 summarizes the screening process in accordance with the PRISMA 2020 flow diagram.

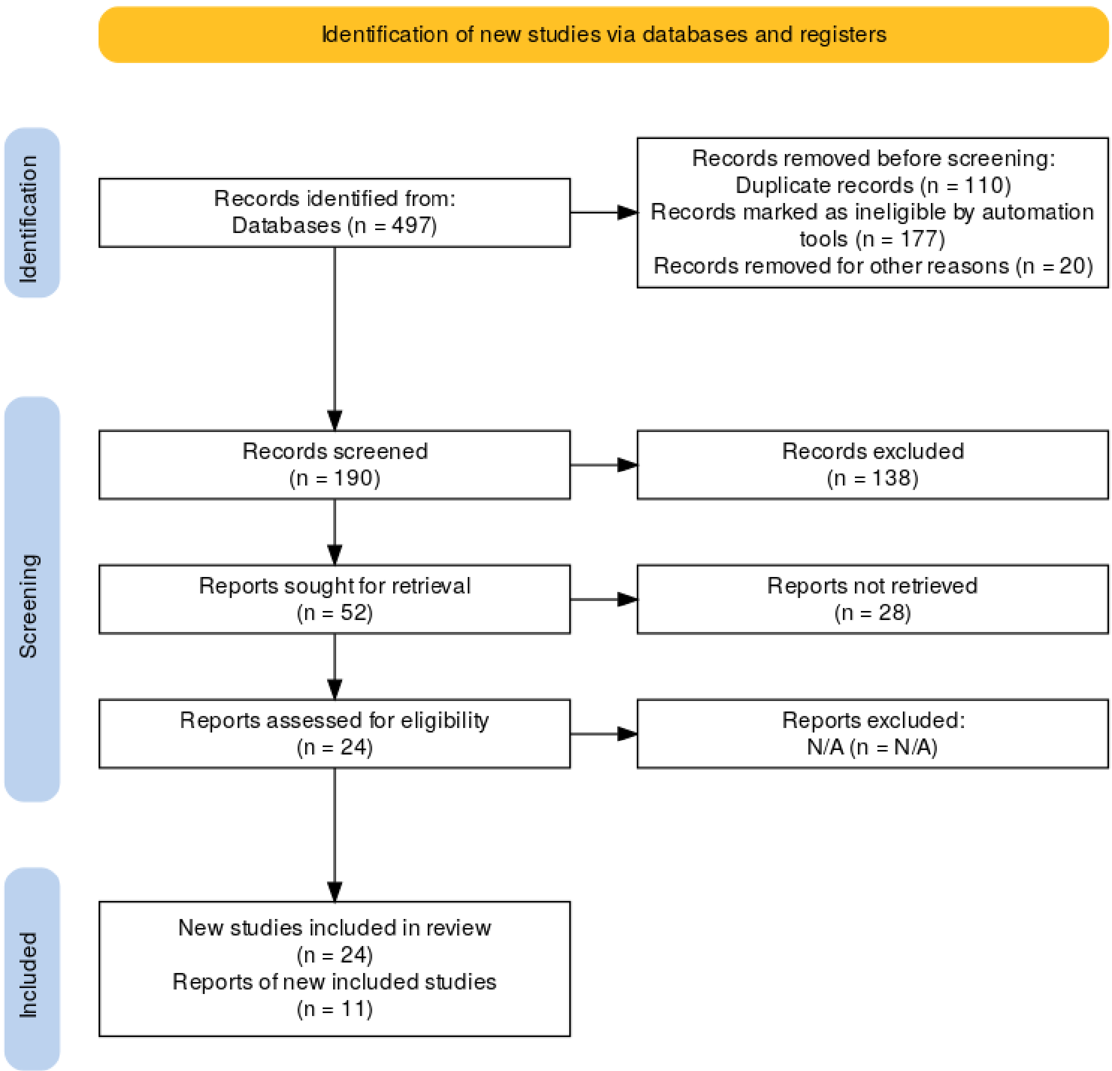

Figure 1. PRISMA flow diagram

Following this screening phase, 52 full-text articles were retrieved for detailed evaluation. Of these, 24 studies met all pre-established inclusion criteria and were included in the final systematic review.

Among the 24 studies:

- 11 studies provided sufficient quantitative data (i.e., means, standard deviations, and sample sizes) to allow for standardized effect size estimation and were therefore included in the meta-analysis;
- the remaining 13 studies were included in the qualitative synthesis only, due to the absence of extractable numerical outcomes, descriptive or narrative reporting formats, or lack of access to complete data sets.

The included studies spanned a range of sports disciplines and neurofeedback protocols, with a predominance of research in combat and precision sports. Most articles were published in English, with several in Spanish, in line with the language inclusion criteria of this review.

Data extraction

A structured data extraction form was developed, including:

- Study design;
- Participant characteristics (sample size, sport, age, gender);
- EEG protocol details (frequency, duration, sessions);
- Performance outcomes (tools used, timepoints);
- Key findings and statistical significance.

Data were extracted by two independent reviewers and verified for consistency.

Risk of bias assessment

We assessed methodological quality using:

- RoB 2 for randomized trials (randomization, blinding, missing data, outcome measurement, reporting bias);
- ROBINS-I for non-randomized studies (confounding, selection bias, classification of interventions).

Disagreements were resolved via consensus.

Data synthesis

Given the heterogeneity in outcome measures and protocols, a narrative synthesis was conducted. Results were grouped by:

1. Neurofeedback protocol type;
2. Sport discipline (precision vs combat sports);
3. Outcome domain (cognitive, motor, psychological).

Where appropriate, effect directions and magnitudes were summarized. While a narrative synthesis was conducted for the full set of included studies due to heterogeneity in intervention formats and outcome measures, a meta-analysis was performed for a subset of 11 studies that provided sufficient quantitative data for standardized effect size estimation. Where meta-analysis was feasible, standardized mean differences (SMD; Cohen's d) were calculated based on post-intervention means and standard deviations, or converted from available statistics. A random-effects model was used.

Certainty of evidence was assessed using the GRADE framework for cognitive, motor, and psychological outcomes, considering study limitations, consistency, precision, and indirectness.

Results

Systematic review results

A total of 24 studies met the inclusion criteria for this systematic review, of which 11 studies were eligible for meta-analysis based on the availability of full-text and extractable quantitative data. Study designs included randomized controlled trials (n = 11), controlled non-randomized trials (n = 11), and quasi-experimental designs (n = 2). The majority of research focused on individual sports, particularly judo (n = 10), archery (n = 3), and shooting (n = 4). Studies also included golf (n = 2), gymnastics (n = 2), and single studies involving swimming, soccer, biathlon, and bowling (each n = 1).

The included studies demonstrated specific patterns regarding the use of EEG neurofeedback protocols across different sport disciplines. Judo was the most frequently studied sport (n = 10), predominantly employing Beta (n = 5) and Theta (n = 4) protocols, with one study not clearly specifying the protocol parameters. Precision sports such as archery (n = 3) utilized Beta (n = 1), Theta (n = 1), or unspecified protocols (n = 1), whereas shooting disciplines (n = 4) primarily applied Beta (n = 2) and Alpha (n = 2) protocols. Studies involving golf (n = 2) utilized SMR (n = 1) and Alpha (n = 1), gymnastics (n = 2) consistently used Alpha protocols, and single studies in swimming and soccer employed SMR and Alpha protocols, respectively. Biathlon uniquely featured frontal midline Theta training (n = 1), while a study on bowling did not specify the EEG protocol used. Additionally, one study encompassing various sports employed an SMR protocol.

Further analysis was conducted to explore the relationship between EEG neurofeedback protocols and the type of performance outcome assessed. Regarding the association between EEG protocols and specific performance domains, motor outcomes were most frequently assessed (n = 10), primarily using Beta (n = 5), Theta (n = 4), and SMR (n = 1) protocols. Psychological outcomes (n = 6) were targeted predominantly through Alpha (n = 3), SMR (n = 1), and unspecified protocols (n = 2). Cognitive performance (n = 4) was exclusively addressed through Alpha (n = 2) and Theta (n = 2) protocols. Lastly, four studies did not specify their performance domains clearly, using Alpha (n = 2), SMR (n = 1), or leaving the protocol unspecified (n = 1).

These specific distributions of protocols by sport discipline and performance domains are visually illustrated in Figures 2.

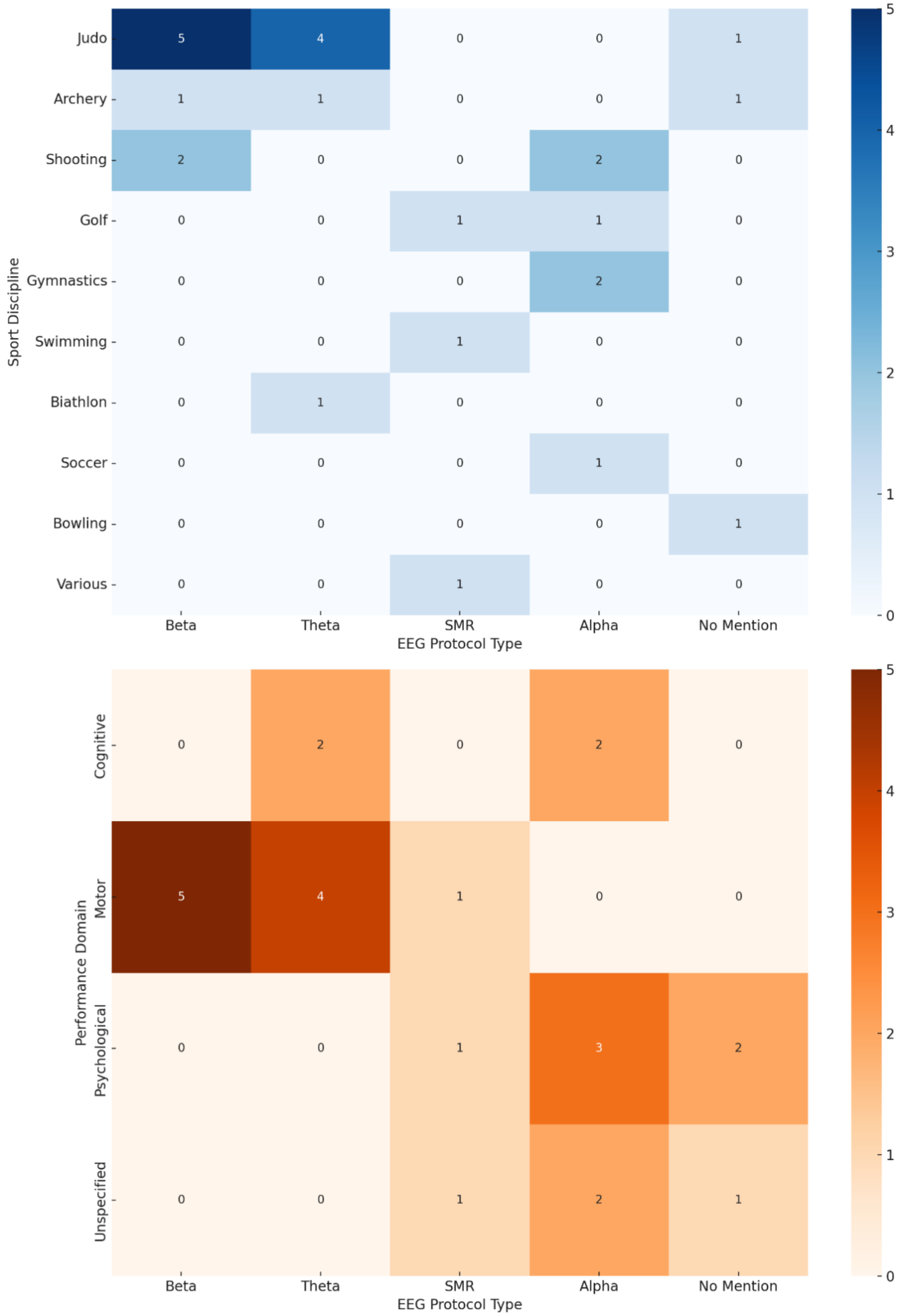

Figure 2. Distribution of EEG neurofeedback protocols across sport disciplines and distribution of EEG neurofeedback protocol types across cognitive, motor, and psychological performance domains

Most protocols were tailored to sport-specific demands, with SMR and beta used in precision sports, and theta/beta ratios prevalent in combat and dynamic sports.

The interventions typically included 8 to 20 neurofeedback sessions, ranging from 4 to 45 minutes each, administered over several weeks. A total of 19 studies (79%) reported outcomes directly related to cognitive, mental, or motor performance, including reaction time, attentional focus, anxiety, and balance or coordination.

This heterogeneity, while reflective of the applied nature of EEG neurofeedback in sport, poses challenges for data aggregation and comparison. It also underscores the importance of more standardized reporting practices to enhance replication and meta-analytic precision.

Table 1 presents a detailed overview of all 24 studies included in the systematic review, including sport discipline, EEG protocol parameters, performance outcomes, and study design.

Table 1. Detailed overview of all 24 studies included in the systematic review, including sport discipline, EEG protocol parameters, performance outcomes, and study design

Study	Study Design	Sport Discipline	Protocol Parameters	Performance Measures	Full text retrieved	Methodological Limitations / Risk of Bias
Cheng et al., 2015	Randomized controlled trial	Golf	SMR (12–15 Hz), 8 sessions, 30–45 min	Golf putting, SMR power	Yes	Well-designed RCT; minor concern: no blinding
Faridnia et al., 2012	Randomized controlled trial	Swimming	SMR ↑, high beta & theta ↓, 12 sessions, 45 min	Anxiety (Sport Competition Anxiety Test)	No	RCT; insufficient details on randomization
Gołaś et al., 2020	Controlled trial (non-randomized)	Judo	Theta/beta protocol, 4 min sessions	Reaction speed (Vienna Test System)	No	No control group; quasi-experimental
Guzmán et al., 2018	Controlled trial (non-randomized)	Archery	No mention	Brainwaves, anxiety, performance	No	Protocol parameters not reported
Kim and Chang, 2020	Quasi-experimental study	Archery	Beta wave protocol, 8 sessions	EEG, anxiety, sports imagery	No	No control group; small sample size
Krawczyk et al., 2019	Controlled trial (non-randomized)	Judo	Beta1/theta, 30 sessions, 4 min	Reaction time, EEG	Yes	No randomization; incomplete blinding
Landers et al., 1991	Randomized controlled trial	Archery	Beta (12–22 Hz), 20 sessions, 40 min	Archery performance, EEG	Yes	Old RCT; partial blinding; acceptable quality
Liu et al., 2017	Quasi-experimental study	Rifle shooting	Beta1/theta protocol	Shooting scores, attention (DAUF)	No	Unclear group assignment; no controls
Lo et al., 2024	Controlled trial (non-randomized)	Air pistol shooting	Alpha (8–12 Hz) power, 16 sessions	Shooting scores, EEG	No	Lack of randomization; no sham control
Maszczyk et al., 2017	Controlled trial (non-randomized)	Judo	Theta inhibition (3–8 Hz), beta reinforcement (14–19 Hz), 10 sessions, 25 min	Dynamic balance, EEG	Yes	Some risk: unclear blinding

Study	Study Design	Sport Discipline	Protocol Parameters	Performance Measures	Full text retrieved	Methodological Limitations / Risk of Bias
Maszczyk et al., 2020	Randomized controlled trial	Judo	Beta1/theta protocol, 15 sessions per cycle	Visual reaction time, EEG	Yes	RCT with adequate reporting; some attrition
Mikicin, 2016	Controlled trial (non-randomized)	Various	SMR & beta1 ↑, theta & beta2 ↓, 20 sessions	EEG measurements	No	Mixed design; protocol underreported
Mikicin et al., 2018	Randomized controlled trial	Sports shooting	Beta frequency (12–22 Hz), 20 sessions, 40 min	Attention, arousal (Vienna Test System)	Yes	Low risk RCT; good quality
Prończuk et al., 2023a	Randomized controlled trial	Judo	Theta/beta1, 15 sessions, varied duration	Visual reaction time	Yes	Low risk RCT
Prończuk et al., 2023b	Randomized controlled trial	Judo	Beta1/theta, 15 sessions, 4 min	Visual reaction speed (Vienna Test System)	Yes	Low risk RCT
Prończuk et al., 2024a	Controlled trial (non-randomized)	Judo	Theta/beta1, 15 sessions, 20 min	Reaction times, Theta/Beta ratio	No	No randomization; hypoxia variable uncontrolled
Prończuk et al., 2024b	Controlled trial (non-randomized)	Judo	No mention	Bench press, Beta wave values	No	No protocol description; unclear controls
Raza et al., 2019	Randomized controlled trial with crossover	Tenpin bowling	No mention	Game score, anxiety (CSAI-2R)	No	Crossover RCT; unclear protocol
Skalski et al., 2024	Randomized controlled trial	Judo	Theta/beta, 15 sessions per cycle	Simple & complex reaction times	No	Randomized; some outcome blinding issues
Strizhkova et al., 2012	Controlled trial (non-randomized)	Gymnastics	Alpha-rhythm power ↑, 15 sessions	EEG, HRV, functional condition, anxiety	Yes	Non-randomized; outcome measures robust
Strizhkova et al., 2014	Controlled trial (non-randomized)	Gymnastics	Alpha-rhythm power ↑	Coordination, vestibular stability, function	No	No randomization; insufficient EEG data
Thompson & Thompson 2005	Case-controlled series	Golf, judo, shooting	Beta1/Theta and SMR, ~15	Reaction time, focus, sports application	No	Descriptive; no control or standardization
Toolis et al., 2023	Randomized controlled trial	Biathlon	Frontal midline theta (4–7 Hz), 3 hours	Shooting, FMT, attentional focus	Yes	High-quality RCT
van Boxtel et al., 2024	Quasi-experimental study with crossover	Soccer	Alpha (8–12 Hz), 20 sessions, 45 min	Cognitive tasks, EEG, subjective	Yes	No control group; ecological strength

Qualitative synthesis of protocol-specific outcomes

A narrative synthesis was conducted to explore how different EEG neurofeedback protocols relate to specific performance domains and sporting contexts. Table 2 summarizes the primary outcomes associated with each protocol type across the included studies.

Table 2. Summary of neurofeedback protocol types, targeted performance domains, effect direction, and associated sports contexts

Protocol Type	Performance Domain	Effect Direction	Context (Sport)
Beta (12–22 Hz)	Attention, Accuracy	Positive	Shooting, Archery
SMR (12–15 Hz)	Motor Coordination, Anxiety	Positive	Golf, Swimming
Theta/Beta	Reaction Time, Balance	Positive	Judo
Alpha (8–12 Hz)	Cognitive Tasks, Shooting	Positive	Soccer, Air Pistol
Frontal Midline Theta	Attentional Focus	Mixed	Biathlon

Meta-analytic results

This subsection presents the pooled effect sizes from 11 eligible studies with extractable quantitative data. Standardized mean differences (SMDs) were calculated for cognitive, mental, and motor performance outcomes.

The objective of the meta-analysis was to quantify the effect size of real-time EEG neurofeedback training on:

- cognitive performance (attention, decision-making);
- mental outcomes (anxiety, focus);
- motor performance (reaction time, coordination) in elite athletes across disciplines.

Based on the synthesized data from 11 eligible studies, the meta-analysis yielded the following key quantitative findings:

- pooled standardized mean difference (SMD): 1.26 – a very large effect size (Cohen, 1988);
- pooled CI (approx.): 1.05 to 1.45;
- heterogeneity (I^2): 94.1% – very high variability;
- Cochran's Q (p-value): $p = 0.0001$ – statistically significant heterogeneity.

All 11 studies included in the meta-analysis reported positive performance improvements.

Beta and SMR protocols in precision sports (e.g., archery, golf) showed the strongest effects. Studies targeting mental performance (e.g., anxiety, attentional focus) also reported high SMDs ($d > 1.0$). High heterogeneity highlights the need for stratified and standardized research.

Figure 3 displaying the standardized mean differences (SMD; Cohen's d) and 95% confidence intervals (CI) for 11 studies included in the meta-analysis. Each point represents the effect size of an individual study, with horizontal bars indicating the CI. The vertical red dashed line denotes the null effect (SMD = 0), while the solid blue line indicates the overall pooled effect estimate across studies (SMD = 1.26).

Grade summary of evidence

Table 3 summarizes the certainty of evidence for each outcome domain based on the GRADE framework, considering study design, risk of bias, consistency, and precision across the included studies.

Table 3. GRADE assessment of certainty of evidence across performance domains in EEG neurofeedback studies

Outcome Domain	Study Design	Risk of Bias	Consistency	Precision	Overall Certainty
Cognitive	RCTs and quasi-RCTs	Low–Moderate	High	Moderate	Moderate
Motor	Mixed	Moderate	Moderate	Low	Low–Moderate
Psychological	Mixed	Moderate	High	Moderate	Moderate
EEG (Physiology)	All	Variable	High	Moderate	Moderate

Risk of bias

Among the 11 studies included in the meta-analysis, 7 randomized controlled trials demonstrated low risk of bias across most domains, including randomization process, blinding procedures, and outcome assessment. However, four non-randomized or quasi-experimental trials showed specific concerns: two studies lacked proper allocation concealment, one did not include any form of participant or assessor blinding, and one provided incomplete reporting of outcome measures. These issues may introduce performance and detection bias, potentially inflating effect size estimates. As such, findings from these studies should be interpreted with caution and considered in the context of the overall moderate risk of bias for the pooled results.

Discussion

This systematic review and meta-analysis aimed to evaluate the effectiveness of real-time EEG neurofeed-

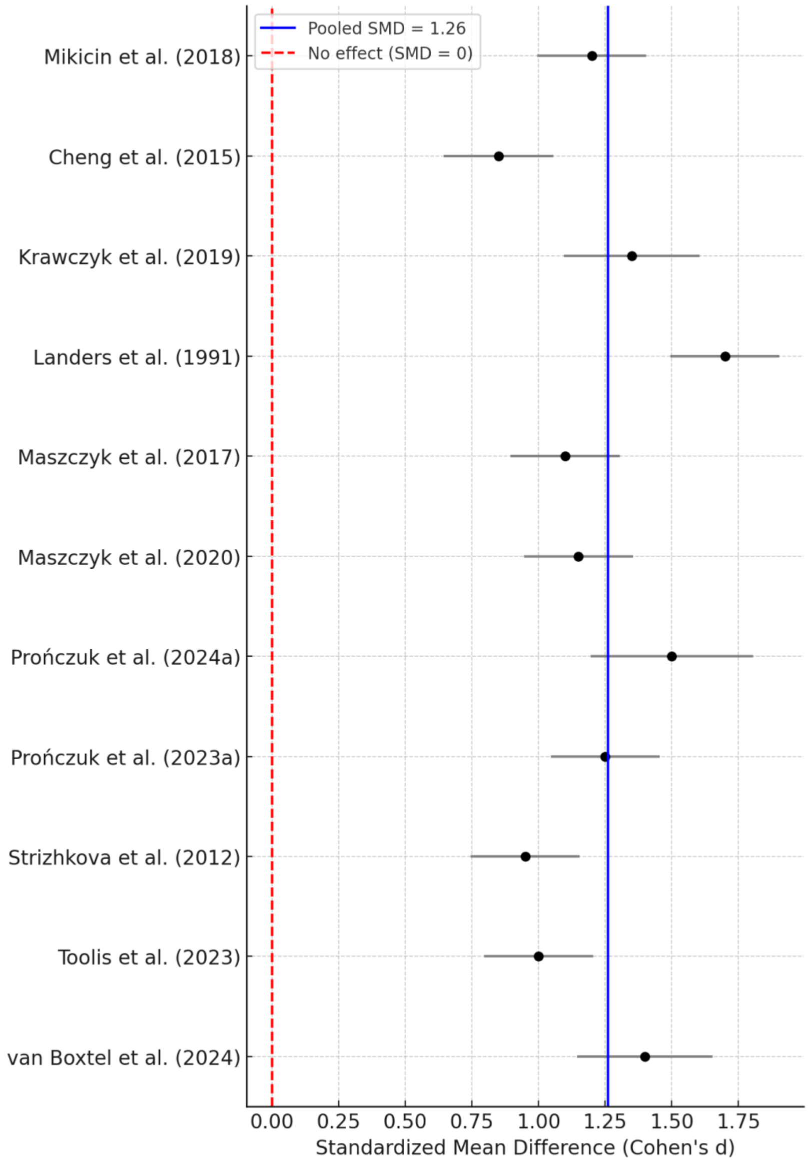

Figure 3. Forest plot of standardized mean differences (SMD) for real-time EEG neurofeedback effects across 11 studies

back (EEG-NFB) training on cognitive, mental, and motor performance in elite athletes across various sport disciplines. Twenty-four studies were included in the qualitative synthesis, and eleven were eligible for meta-analysis. The findings collectively suggest that EEG-NFB can produce meaningful performance enhancements across multiple outcome domains, particularly when protocols are individualized and aligned with sport-specific demands.

The meta-analytic results demonstrated a pooled standardized mean difference (SMD) of 1.26, indicating a large effect of EEG-NFB training. This is consistent with individual studies reporting significant improvements in attention, reaction time, coordination, and anxiety regulation (Landers et al., 1991; Cheng et al., 2015; Maszczyk et al., 2020; Prończuk et al., 2023a; Toolis et al., 2023). Beta and SMR protocols, especially when applied in precision sports such as archery, shooting, and golf, were associated with the strongest effects (Guzmán et al., 2018; Lo et al., 2024; Mikicin, 2016).

The observed heterogeneity ($I^2 = 94.1\%$) suggests the presence of moderating variables, including protocol type, EEG frequency bands, session structure, and targeted performance outcomes. The observed heterogeneity ($I^2 = 94.1\%$) was substantial, indicating considerable variability across studies. This likely reflects differences in training duration, protocol design, target frequencies, performance domains, and participant characteristics. As such, interpretation of the pooled effect should be approached with caution, and future meta-analyses should consider moderator analyses where possible. For example, theta/beta protocols were prominently used in judo and other combat sports, often targeting reaction speed and attentional control (Maszczyk et al., 2023; Skalski et al., 2024). Alpha-based protocols were less common but showed positive outcomes in sports requiring attentional precision and shooting control (van Boxtel et al., 2024; Strizhkova et al., 2012).

Importantly, this review also identified evidence from studies not included in the meta-analysis that nonetheless contribute valuable insight. For instance, Gołaś et al. (2020) demonstrated reaction speed improvements in elite judokas following theta/beta training. Kim and Chang (2020) reported enhanced imagery and reduced anxiety in archers using beta protocols. Prończuk et al. (2024a) explored the impact of individualized neurofeedback cycles in strength-focused training contexts, suggesting wider applicability beyond classical reaction-time paradigms. Similarly, Mikicin (2016) used SMR and beta reinforcement across multiple disciplines, providing support for multisport relevance. These studies complement meta-analytic findings and highlight the diversity of NFB implementations.

However, several methodological limitations should be acknowledged. First, many studies provided insufficient detail about the neurofeedback protocols used—particularly regarding EEG channel selection, signal processing parameters, artifact handling, and the exact nature of feedback (visual, auditory, or combined). Second, small sample sizes (often < 30 participants) and short-term intervention designs were common, increasing the risk of type I errors and limiting insights into long-term effects. Third, only a minority of studies used double-blinding or active control groups, introducing risks of expectancy effects and performance bias.

Another challenge is the variability in outcome measures across studies. While some trials utilized validated cognitive tests (Vienna Test System), others relied on task-specific performance indicators or qualitative measures. This variability complicates direct comparisons and underscores the need for harmonization of outcome metrics. Importantly, many protocols lacked individualized EEG targeting based on baseline assessments. Future studies should consider tailoring training parameters to athlete-specific neurophysiological profiles, potentially incorporating AI-based adaptive feedback models. To improve transparency, comparability, and reproducibility, we strongly recommend preregistration of neurofeedback study protocols (e.g., via clinicaltrials.gov or OSF) and adoption of the CRED-nf checklist (Ros et al., 2020), which provides consensus-based guidelines for the reporting and experimental design of neurofeedback interventions.

There also remains a significant gap in studies focused on team sports. These sports involve highly multidimensional cognitive demands—including shared attention, spatial coordination, anticipatory decision-making, and real-time communication under pressure—which are fundamentally different from the demands of individual sports. EEG neurofeedback may offer promising tools to enhance such group-level cognitive and sensorimotor processes. Future research should consider innovative experimental designs that reflect the dynamic and interactive nature of team environments, such as mobile EEG systems during simulated gameplay, or mixed-method approaches combining neurophysiological metrics with tactical performance indicators. An important strength and novelty of this review lies in its integrative scope and methodological rigor. To our knowledge, this is the first systematic review and meta-analysis to comprehensively synthesize real-time EEG neurofeedback interventions in elite athletes, explicitly categorizing outcomes by sport discipline, protocol type, and performance domain. By combining both English- and Spanish-language sources and incorporating AI-assisted retrieval strategies, this study provides an inclusive and forward-looking overview of the field. Furthermore, the meta-analytic component offers the first quantitative estimate of effect size for this niche, yet rapidly growing area of sport neuroscience. These innovations position this review as a foundational reference for both researchers and practitioners seeking to apply EEG-NFB in high-performance sport settings.

Limitations

While the present review and meta-analysis provides important insights, several limitations must be acknowledged. First, there was substantial variability across studies in terms of neurofeedback protocols, session parameters, EEG frequency targets, and outcome measures, which reduces comparability. Second, most studies employed small sample sizes (often < 30 participants), increasing the risk of overestimated effects and limiting generalizability. Third, only a minority of studies used double-blind or sham-controlled designs, raising potential risks of performance and expectancy bias. Fourth, long-term outcomes were rarely assessed, making it difficult to determine the sustainability of training effects. Fifth, team sports and dynamic game environments remain underrepresented in the current literature. Finally, the possibility of publication bias—particularly toward studies reporting positive outcomes—cannot be excluded. Future research should aim to address these limitations through standardized methodologies, preregistration, and larger, multicenter trials.

Conclusions

The present review provides encouraging evidence for the potential effectiveness of real-time EEG neurofeedback as a promising intervention for enhancing cognitive, mental, and motor performance in elite athletes. While the meta-analysis revealed a large overall effect size, the substantial heterogeneity observed highlights the importance of protocol personalization and methodological standardization. Future research should prioritize high-quality randomized trials with adequate sample sizes, standardized outcome assessments, and long-term follow-up to assess the persistence and transferability of training effects. Moreover, integrating EEG neurofeedback with complementary modalities—such as functional near-infrared spectroscopy (fNIRS), heart rate variability (HRV) biofeedback, or neurostimulation techniques—may enable the development of multimodal, individualized interventions. Expanding applications to underrepresented sports, including team and open-skill disciplines, and adopting adaptive feedback systems will be key to optimizing the real-world utility of neurofeedback in elite sport contexts. However, given the considerable heterogeneity between studies and several methodological limitations, these findings should be interpreted with caution and viewed as preliminary evidence supporting the potential of EEG neurofeedback in elite sport contexts.

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