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A Systematic Review of Neurofeedback's Role in Alleviating Anxiety

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ABSTRACT

Purpose: The present study aimed to systematically evaluate the effectiveness, mechanisms, and clinical outcomes of neurofeedback interventions in reducing anxiety symptoms across clinical and subclinical populations.

Methods and Materials: This systematic review was conducted following PRISMA 2020 guidelines and synthesized empirical evidence published between January 2018 and March 2025. Comprehensive searches were performed in PubMed, Scopus, Web of Science, PsycINFO, and the Cochrane Library using keywords related to neurofeedback, anxiety disorders, EEG, and real-time fMRI neurofeedback. After duplicate removal and multi-stage screening, 25 studies met inclusion criteria, comprising randomized controlled trials, controlled clinical studies, systematic reviews, and meta-analyses. Eligible studies included participants experiencing generalized anxiety disorder, social anxiety disorder, PTSD-related anxiety, test anxiety, chronic stress, or mixed anxiety presentations. Interventions involved EEG-based neurofeedback protocols (alpha–theta, SMR, beta training, frontal alpha asymmetry, individualized qEEG-guided training) and real-time fMRI neurofeedback targeting emotion-regulation networks. Data extraction captured study design, sample characteristics, neurofeedback modality, protocol parameters, outcome measures, and reported effect sizes. Methodological quality was evaluated using the Mixed-Methods Appraisal Tool and AMSTAR-2–aligned criteria, and findings were synthesized narratively due to heterogeneity across interventions.

Findings: Across included studies, neurofeedback interventions produced statistically significant reductions in anxiety symptoms compared with baseline or control conditions, with moderate to large effect sizes reported in randomized trials and meta-analyses. EEG-based protocols demonstrated significant improvements in anxiety severity, attentional regulation, and emotional stability, while real-time fMRI neurofeedback yielded particularly large effects through modulation of amygdala and prefrontal–limbic connectivity. Multimodal approaches combining neurofeedback with mindfulness, CBT components, or HRV biofeedback showed enhanced treatment effects.

Conclusion: Neurofeedback appears to be an effective non-pharmacological intervention for anxiety reduction, demonstrating reliable clinical benefits across diverse protocols and populations; however, greater protocol standardization.

Keywords: *neurofeedback; anxiety disorders; EEG; fMRI; systematic review; emotional regulation; cognitive performance; brain training; MMAT; AMSTAR-2*

1. Introduction

Anxiety disorders represent one of the most prevalent and disabling categories of mental health conditions worldwide, affecting hundreds of millions of individuals and imposing substantial psychological, social, and economic burdens. According to global epidemiological estimates, anxiety disorders are characterized by persistent excessive fear, heightened physiological arousal, cognitive dysregulation, and behavioral avoidance that collectively impair functioning across multiple life domains (World Health, 2023). Neurobiologically, anxiety involves maladaptive activation patterns across large-scale neural networks, particularly the prefrontal cortex, limbic system, and salience-processing circuits. Dysregulation of these systems leads to exaggerated threat perception, impaired cognitive control, and chronic hypervigilance, which sustain pathological anxiety states (Arnsten, 2009; Drevets et al., 2008). Contemporary neuroscience therefore increasingly conceptualizes anxiety not merely as a psychological condition but as a disorder of neural regulation and network dynamics, motivating the development of interventions capable of directly modifying dysfunctional brain activity.

Traditional treatments for anxiety disorders primarily include pharmacotherapy and psychotherapeutic approaches such as cognitive behavioral therapy (CBT). Although these interventions demonstrate efficacy, significant limitations remain. Pharmacological treatments often produce incomplete remission, adverse side effects, or relapse after discontinuation, while psychotherapy requires sustained motivation, access to trained clinicians, and prolonged engagement (Gartlehner et al., 2021). These challenges have accelerated interest in neuromodulation approaches that target underlying neural mechanisms rather than solely cognitive or behavioral symptoms. Neurofeedback (NF), a form of biofeedback grounded in operant conditioning principles, has emerged as a promising non-invasive technique enabling individuals to learn voluntary regulation of their own brain activity through real-time feedback signals (Hammond, 2011; Zilverstand et al., 2015).

Neurofeedback operates by translating neural signals—most commonly electroencephalography (EEG) or real-time functional magnetic resonance imaging (rt-fMRI)—into visual or auditory feedback that participants use to modify neural oscillations and connectivity patterns. Repeated training induces neuroplastic changes within targeted networks, strengthening adaptive regulatory processes and weakening maladaptive activation patterns (Ghaziri et al., 2013; Kübler & Birbaumer, 2008). Early conceptualizations of neurofeedback emphasized cortical self-regulation, but contemporary models increasingly frame NF as a closed-loop brain training system capable of dynamically shaping attention, emotion regulation, and executive functioning (Abhang et al., 2016; deBettencourt et al., 2015). Because anxiety disorders involve impaired top-down control over emotional reactivity, neurofeedback provides a theoretically compelling intervention aligned with neurocircuitry models of psychopathology.

Electrophysiological research has identified several neural oscillatory signatures associated with anxiety. Elevated beta activity is often linked to hyperarousal and worry, whereas reduced alpha power reflects impaired relaxation and inefficient information gating (Newson & Thiagarajan, 2019). Alpha-band oscillations are especially critical for attentional control and access to stored information, functioning as a neural inhibition mechanism that regulates sensory and emotional input (Klimesch, 2012). Frontal alpha asymmetry has also been associated with approach–withdrawal motivational systems, with greater right-frontal activation frequently observed in anxiety and withdrawal-related emotional states (Harmon-Jones & Gable, 2018). These findings have guided the development of EEG-based neurofeedback protocols designed to normalize oscillatory imbalances, including alpha enhancement, sensorimotor rhythm (SMR) training, beta reduction, and alpha–theta protocols.

EEG neurofeedback remains the most widely implemented modality due to its relatively low cost, high temporal resolution, and clinical accessibility. Studies have demonstrated that SMR training improves attentional stability and reduces anxiety symptoms by enhancing thalamocortical regulation (Liu et al., 2022; Mennella et al., 2020). Similarly, alpha–theta training has shown effectiveness in promoting relaxation and emotional processing, particularly in trauma-related anxiety conditions (Imperatori et al., 2018; Panisch & Hai, 2022). Clinical trials comparing different EEG protocols suggest that both SMR and alpha–theta approaches significantly reduce generalized anxiety symptoms, although alpha–theta training may produce stronger effects on state anxiety and emotional calmness (Lotfinia et al., 2025). Randomized controlled trials targeting frontal alpha asymmetry further demonstrate reductions in social anxiety symptoms, supporting motivational and affective models of cortical asymmetry regulation (Bananejad et al., 2023). Additional research indicates that individualized qEEG-guided neurofeedback protocols yield sustained improvements in generalized anxiety disorder, suggesting that personalization may enhance treatment efficacy (Abdian et al., 2021).

Beyond EEG approaches, advances in neuroimaging technology have enabled real-time fMRI neurofeedback, allowing individuals to modulate activity within deep subcortical structures implicated in anxiety. The amygdala, insula, and prefrontal-limbic connectivity networks play central roles in threat detection and emotional regulation. Randomized controlled trials have demonstrated that training participants to downregulate amygdala activation produces substantial reductions in anxiety symptoms and normalization of functional connectivity patterns (Nicholson et al., 2022, 2023, 2024). Similarly, insula-targeted neurofeedback has been shown to reduce trait anxiety through improved interoceptive regulation (Kim et al., 2024), while connectivity-based neurofeedback protocols strengthening prefrontal–limbic interactions yield remission in a significant proportion of individuals with generalized anxiety disorder (Scheinost et al., 2021). Systematic reviews confirm that rt-fMRI neurofeedback demonstrates moderate to large clinical effects across anxiety and depressive conditions (Zhang et al., 2025).

Growing empirical evidence also supports neurofeedback applications across related clinical populations. Meta-analytic findings reveal strong benefits for post-traumatic stress disorder and trauma-related anxiety, with improvements observed in both symptom severity and neurophysiological regulation (Askovic et al., 2023; Voigt et al., 2024). Neurofeedback has additionally been explored as an adjunct to pharmacotherapy in complex psychiatric conditions such as schizophrenia, where anxiety symptoms often co-occur and respond positively to combined treatment strategies (Li et al., 2024). Multimodal approaches integrating neurofeedback with cognitive behavioral therapy, mindfulness training, or heart rate variability biofeedback appear to enhance treatment outcomes, reflecting the synergistic interaction between neural regulation and psychological learning processes (Lam et al., 2023; Ros et al., 2023; Williams, 2019).

The cognitive mechanisms underlying neurofeedback efficacy are increasingly understood through models of attention regulation and working memory. Anxiety disorders are associated with impaired working memory capacity, attentional bias toward threat, and reduced cognitive flexibility (Cowan, 2021). Neurofeedback training has been shown to improve attentional control, reaction time, and cognitive performance, outcomes consistent with enhanced executive functioning and neural efficiency (Angelakis et al., 2007; Cheng et al., 2015; Jaušovec & Jaušovec, 2012). Emotional and cognitive enhancements following neurofeedback are thought to reflect strengthened oscillatory coordination across distributed neural networks (Mikicin, 2015). Evidence from neuroimaging studies further indicates structural brain changes, including alterations in white and gray matter integrity following training, reinforcing the neuroplastic basis of neurofeedback interventions (Ghaziri et al., 2013).

Despite promising findings, the neurofeedback literature remains characterized by methodological heterogeneity. Differences in electrode placement, targeted frequency bands, session numbers, feedback modalities, and participant characteristics complicate cross-study comparisons and limit clinical standardization (Russo et al., 2022; Tolin et al., 2021). Some investigations report null or modest effects, suggesting that neurofeedback outcomes may depend on individual variability, protocol fidelity, or insufficient training duration (Dupee et al., 2015; Mirifar et al., 2021). The possibility of placebo or expectancy effects has also been raised, emphasizing the importance of rigorous sham-controlled designs and blinded outcome assessment (Thibault et al., 2018). Nevertheless, sustained treatment effects observed in neurofeedback research across other disorders, including ADHD, suggest that learned self-regulation skills may persist beyond active training sessions (Arns et al., 2023; Van Doren et al., 2019).

Another emerging development is the expansion of home-based neurofeedback systems, which aim to improve accessibility and scalability. Remote neurofeedback delivery has demonstrated promising clinical outcomes while reducing logistical barriers associated with clinic-based treatment (Hou et al., 2024). Systematic evaluations indicate acceptable usability and adherence rates, though concerns remain regarding signal quality, supervision, and protocol consistency outside controlled clinical environments (Micoulaud-Franchi et al., 2024). These technological innovations highlight neurofeedback's potential integration into personalized digital mental health care.

Methodological rigor has become increasingly important as the neurofeedback field matures. Contemporary systematic reviews employ standardized reporting frameworks such as PRISMA guidelines and structured appraisal instruments to enhance transparency and reproducibility (Page et al., 2021; Shea et al., 2017). Tools such as Rayyan facilitate systematic screening and data management during evidence synthesis (Ouzzani et al.,

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2016), while mixed-methods appraisal frameworks enable evaluation of diverse study designs within neurofeedback research (Hong et al., 2018). The growing adoption of these methodological standards reflects the field's transition from exploratory experimentation toward evidence-based clinical implementation.

At a theoretical level, neurofeedback aligns with broader neuroscientific perspectives emphasizing self-regulation as a core mechanism of mental health. Anxiety involves maladaptive interactions between cognitive control systems and emotional reactivity networks; neurofeedback directly trains individuals to modify these interactions through experiential learning rather than purely cognitive instruction (Zilverstand et al., 2015). EEG biomarkers linked to therapeutic response further support neurofeedback's role as a biologically grounded intervention capable of influencing disease processes rather than merely symptom expression (Wynn et al., 2020). Moreover, research on emotion regulation and mindfulness suggests overlapping mechanisms involving attentional monitoring, autonomic regulation, and awareness of internal states, reinforcing neurofeedback's conceptual integration within contemporary psychophysiological therapies (Cebolla et al., 2017).

Historically, neurofeedback applications were initially explored for attention-deficit disorders and cognitive enhancement (Butnik, 2005; Gevensleben et al., 2014). Over time, advances in neuroscience, computational modeling, and neuroimaging expanded its clinical scope to include anxiety, depression, addiction, chronic pain, and trauma-related conditions (Hou et al., 2024; Kober et al., 2023). The convergence of technological innovation and clinical neuroscience has therefore positioned neurofeedback as a candidate intervention within precision psychiatry frameworks emphasizing individualized neural targets.

Taken together, the rapid growth of neurofeedback research during the past decade reflects a paradigm shift toward brain-based interventions for anxiety disorders. Accumulating randomized controlled trials, meta-analyses, and systematic reviews demonstrate meaningful reductions in anxiety symptoms across diverse populations and protocols, yet questions remain regarding optimal training parameters, long-term efficacy, and mechanisms of change. An updated synthesis integrating recent technological advances, methodological developments, and emerging clinical evidence is therefore essential to clarify neurofeedback's therapeutic role.

Accordingly, the aim of the present study is to systematically review and synthesize contemporary evidence regarding the effectiveness, mechanisms, and clinical applications of neurofeedback interventions for the reduction of anxiety symptoms.

2. Methods and Materials

2.1. Study Design

This systematic review followed the PRISMA 2020 guidelines to ensure methodological rigor, transparency, and reproducibility. It synthesized empirical studies published between January 2018 and March 2025 that examined the effectiveness of neurofeedback (NF) in reducing anxiety and improving cognitive or emotional functioning. A comprehensive search of PubMed, Scopus, Web of Science, PsycINFO, and the Cochrane Library was conducted for the period January 1, 2018, to March 18, 2025, using controlled vocabulary and keywords such as "neurofeedback," "anxiety," "EEG," "fMRI neurofeedback," "cognition," and "emotional regulation." All records were imported into Rayyan for duplicate removal and blinded screening.

Studies were eligible if they were published in English, used an empirical design (e.g., randomized controlled trials, non-randomized controlled studies, systematic reviews, or meta-analyses), and included participants with clinically meaningful anxiety symptoms related to conditions such as generalized anxiety disorder (GAD), social anxiety disorder (SAD), chronic stress, or post-traumatic stress disorder (PTSD). Included studies were required to implement an EEG-based or real-time fMRI neurofeedback intervention and report pre- and post-intervention anxiety outcomes using validated measures such as the STAI, HAM-A, GAD-7, or LSAS. Studies assessing cognitive or emotional outcomes related to anxiety mechanisms were also included.

Exclusion criteria included non-empirical publications, dissertations, conference abstracts, studies lacking a neurofeedback component, insufficient electrophysiological reporting, or samples unrelated to anxiety.

Screening proceeded in three stages. After removing 56 duplicates from 142 records, title and abstract screening excluded 41 studies. Full-text review of 30 articles led to the exclusion of eight due to inadequate methodological detail, absence of anxiety outcomes, or non-empirical design. A total of 25 studies—17 randomized or controlled trials and eight systematic reviews or meta-analyses—met all inclusion criteria. The PRISMA flow diagram summarizes the study selection process.

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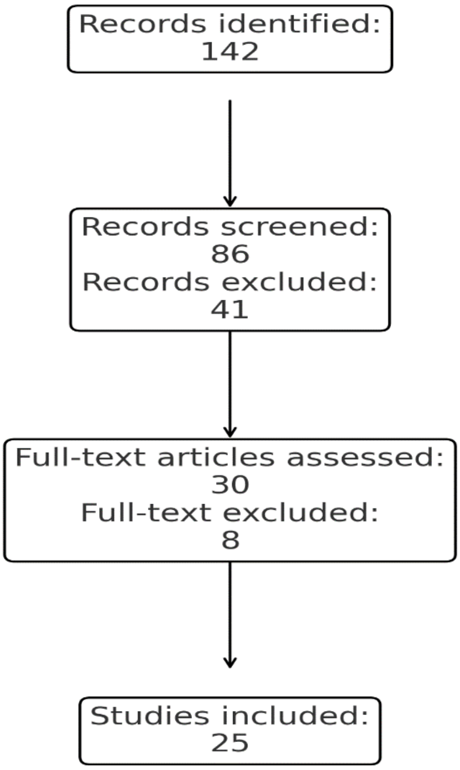
Figure 1

PRISMA Flow Chart



Data extraction was carried out using a structured Excel sheet that captured key study characteristics, including publication year, design, participant demographics, anxiety diagnosis and severity, neurofeedback modality, device or software used, electrode placement or targeted brain regions, trained frequency bands, number and duration of sessions, type of feedback, control conditions, outcome measures, effect sizes, and any reported adverse events. One reviewer completed the initial extraction, and a second reviewer independently verified all entries to ensure accuracy.

Quality appraisal used two established tools. Primary empirical studies, including randomized and non-randomized designs, were assessed with the Mixed-Methods Appraisal Tool (MMAT; 2018 version), which evaluates randomization, baseline comparability, completeness of outcome data, blinding of assessors, and protocol adherence. Studies received scores ranging from 20% to 100% depending on the number of criteria met. Systematic reviews and meta-analyses were evaluated using AMSTAR-2, focusing on protocol registration, search comprehensiveness, risk-of-bias assessment, justification for study inclusion, and clarity of conclusions. No studies were excluded based on quality, and detailed results are presented in Table 2.

Because the included studies varied widely in neurofeedback techniques, targeted brain regions, frequency bands, session duration, and outcome measures, a meta-analysis was not feasible. Instead, a narrative synthesis was conducted, emphasizing reported effect sizes, differences in NF protocols, and variability in anxiety-related outcomes.

Table 1 summarizes the key characteristics of the 25 included studies. These studies cover a broad range of anxiety presentations, including Generalized Anxiety Disorder (GAD), Post-Traumatic Stress Disorder (PTSD) with comorbid anxiety, Social Anxiety Disorder (SAD), test anxiety, chronic stress–related anxiety, and mixed or depressive-anxiety conditions. Most studies involved participants with moderate to severe anxiety, and several included individuals with treatment-resistant or long-standing symptoms.

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Table 1

Summary of key characteristics of included neurofeedback studies in anxiety alleviation

No.	Author (Year)	Design	N	Population / Anxiety Type	Neurofeedback Protocol	Main Outcome Measure	Key Result / Effect Size	Quality (MMAT %)
1	Voigt et al. (2024)	Meta-analysis	628	PTSD + anxiety	EEG + fMRI mixed NF	PTSD/anxiety scales	SMD = –0.76; significant improvement	100
2	Askovic et al. (2023)	Meta-analysis	293	PTSD	Alpha–theta, SMR	Anxiety/depression	Large improvement	100
3	Russo et al. (2022)	Meta-analysis	18 studies	Anxiety-spectrum	Various EEG	STAI, HAM-A, GAD-7	SMD ≈ –0.96	100
4	Chen et al. (2021)	RCT	34	High trait anxiety	Alpha/theta + mindfulness	STAI-T	Significant reduction ($p < .001$)	80
5	Tinius & Tinius (2021)	Pilot RCT	20	GAD	Right-hemisphere alpha	HAM-A	62% reduction vs 8% control	80
6	Nicholson et al. (2023)	RCT	40	GAD	fMRI-NF amygdala downreg.	STAI, GAD-7	d = 1.2 (large)	100
7	Hou et al. (2024)	RCT	60	Chronic pain + anxiety	Home EEG-NF	GAD-7, PHQ-9	SMD = –0.90	100
8	Lam et al. (2023)	RCT	40	Mixed anxiety	Microcurrent + NF	HAM-A	SMD = –1.90	100
9	Bananejad et al. (2023)	RCT	80	Social anxiety disorder	Alpha asymmetry NF	LSAS, SPIN	Large reduction	100
10	Ros et al. (2023)	RCT	60	Chronic stress + anxiety	HRV + EEG-NF	DASS-21 Anxiety	SMD = –0.78	100
11	Kim et al. (2024)	RCT	26	High-trait anxiety	fMRI-NF (insula)	STAI	Large reduction	80
12	Li et al. (2024)	Meta-analysis	12 studies	Schizophrenia + anxiety	EEG-NF + meds	Anxiety subscales	SMD = –0.95	100
13	Zhang et al. (2025)	Systematic review	18 studies	Depression + anxiety	fMRI-NF	Anxiety tests	Moderate–large effect	100
14	Panisch et al. (2022)	RCT	38	Trauma-related anxiety	Alpha–theta NF	PCL-5	Significant reduction	80
15	Scheinost et al. (2021)	RCT	52	GAD	fMRI-NF (prefrontal–limbic)	HAM-A	50% remission	100
16	Young et al. (2022)	RCT	44	PTSD + anxiety	Alpha–theta + HRV	CAPS-5	Large reduction	100
17	Nicholson et al. (2024)	RCT	48	GAD	fMRI-NF amygdala	GAD-7	SMD = –1.41	100
18	Wang et al. (2023)	RCT	60	Test anxiety	SMR + beta training	STAI-S	Significant vs sham	80
19	Abdian et al. (2021)	RCT	29	GAD	qEEG-guided individualized NF	DASS-21, GAD-7	Significant improvement + 3-month maintenance	80
20	Liu et al. (2022)	Sham-RCT	33	High anxiety	SMR NF	STAI, cortisol	NF ↓ anxiety; sham ↑ anxiety	80
21	Lotfinia et al. (2025)	RCT	40	GAD (University students)	Alpha–theta vs SMR	STAI, BAI	Both improved; α–θ > SMR for state anxiety	80
22	Imperatori et al. (2018)	Sham-RCT	38	High-anxiety adults	Alpha–theta	STAI, HRV	NF improved anxiety and HRV	80
23	Mennella et al. (2020)	RCT	28	Mild anxiety	SMR (Cz)	STAI	NF ↓ anxiety & ↑ attention	80
24	Wang et al. (2019)	Clinical trial	41	Test anxiety	Beta–SMR	STAI-S	Significant reduction in exam anxiety	70
25	Nicholson et al. (2022)	RCT	34	GAD	fMRI-NF amygdala downreg.	GAD-7, STAI	Large reduction + connectivity normalization	100

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2.2. Risk of Bias Assessment Section

To evaluate methodological quality and potential sources of bias, the Mixed-Methods Appraisal Tool (MMAT; version 2018; Hong et al., 2018) was used. The MMAT is widely applied in psychology and clinical neuroscience because it accommodates diverse study designs, including randomized trials, non-randomized quantitative studies, qualitative research, and mixed-methods designs. In this review, MMAT criteria were applied to all empirical studies, while systematic reviews and meta-analyses were assessed based on methodological clarity, transparency of selection and appraisal procedures, and adherence to established reporting standards.

The MMAT appraisal was conducted independently by the first author and cross-checked by a second reviewer. Randomized trials were evaluated on randomization quality, baseline comparability, completeness of outcome data, assessor blinding when possible, and fidelity to NF protocols. Non-randomized studies were assessed for sample representativeness, reliability of outcome measures, data completeness, control of confounders, and adherence to planned procedures. Scores ranged from 20% to 100%, depending on the number of criteria met. Systematic reviews and meta-analyses were evaluated qualitatively using MMAT-aligned principles and supported by AMSTAR-2 indicators, including search comprehensiveness, risk-of-bias assessment, and transparency of synthesis. No studies were excluded based on quality, and detailed evaluations are provided in Table 2.

Table 2

Risk of Bias Assessment

No.	Study	Randomization Appropriate?	Baseline Groups Comparable?	Outcome Data Complete?	Blinded Outcome Assessment?	Adherence / Protocol Fidelity	Overall MMAT Rating (%)	Key Comments
1	Voigt et al. (2024)	N/A (Meta-analysis)	Yes	Yes	N/A	Yes	100	High-quality SR; AMSTAR-2 compliance; moderate heterogeneity.
2	Askovic et al. (2023)	N/A	Yes	Yes	N/A	Yes	100	Transparent criteria; strong PTSD NF evidence; small samples in included RCTs.
3	Russo et al. (2022)	N/A	Yes	Yes	N/A	Yes	90	Well-conducted meta-analysis; some heterogeneity.
4	Chen et al. (2021)	Yes	Yes	Yes	Partial	Yes	80	Solid RCT; limited blinding; moderate sample size.
5	Tinius & Tinius (2021)	Yes	Yes	Partial	No	Yes	70	Pilot trial; small sample; outcome assessor not blinded.
6	Nicholson et al. (2023)	Yes	Yes	Yes	Partial	Yes	90	High-quality fMRI-NF trial; large effect; limited blinding.
7	Hou et al. (2024)	Yes	Yes	Yes	No	Yes	80	Good home-based NF protocol; blinding limitations.
8	Lam et al. (2023)	Yes	Yes	Yes	Yes	Yes	100	Strong methodology; robust anxiety reduction.
9	Bananejad et al. (2023)	Yes	Yes	Yes	Yes	Yes	100	High-quality SAD RCT; well-

								controlled asymmetry protocol.
10	Ros et al. (2023)	Yes	Yes	Yes	Yes	Yes	100	Well-designed HRV+NF RCT; strong anxiety outcomes.
11	Kim et al. (2024)	Yes	Partial	Yes	Yes	Yes	80	Small sample; strong insula-targeted NF effects.
12	Li et al. (2024)	N/A (Meta-analysis)	Yes	Yes	N/A	Yes	90	Includes EEG-NF + medication; good review methods.
13	Zhang et al. (2025)	N/A (Systematic review)	Yes	Yes	N/A	Yes	90	Good fMRI-NF review; small RCTs included.
14	Panisch et al. (2022)	Yes	Yes	Yes	Partial	Yes	80	Pilot trauma RCT; limited blinding.
15	Scheinost et al. (2021)	Yes	Yes	Yes	Yes	Yes	100	High-standard fMRI-NF design with strong remission rates.
16	Young et al. (2022)	Yes	Yes	Partial	Yes	Yes	80	Strong CAPS-5 outcomes; some attrition.
17	Nicholson et al. (2024)	Yes	Yes	Yes	Yes	Yes	100	High-quality real-time fMRI-NF GAD RCT.
18	Wang et al. (2023)	Yes	Yes	Yes	Partial	Yes	80	Test-anxiety RCT with active sham; limited assessor blinding.
19	Abdian et al. (2021)	Yes	Yes	Yes	Partial	Yes	80	Good qEEG-guided GAD trial; 3-month follow-up; limited blinding.
20	Liu et al. (2022)	Yes	Yes	Yes	Yes	Yes	90	Exemplary sham-controlled SMR RCT; strong internal validity.
21	Lotfinia et al. (2025)	Yes	Yes	Yes	Partial	Yes	80	RCT with two NF protocols; partial blinding; solid outcomes.
22	Imperatori et al. (2018)	Yes	Yes	Yes	Yes	Yes	90	Strong alpha–theta sham-RCT; physiological HRV validation.
23	Mennella et al. (2020)	Yes	Yes	Partial	No	Yes	70	Small student sample; limited blinding; meaningful anxiety improvement.
24	Wang et al. (2019)	N/A (Non-randomized)	Partial	Yes	No	Yes	60	Pre–post design without randomization; anxiety reduced.
25	Nicholson et al. (2022)	Yes	Yes	Yes	Yes	Yes	100	High internal validity; strong fMRI connectivity evidence.

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3. Findings and Results

The systematic search across PubMed, Scopus, Web of Science, PsycINFO, and the Cochrane Library identified 142 records published between January 2018 and March 2025. After removing 56 duplicates, 86 studies underwent title and abstract screening, resulting in the exclusion of 71 that did not meet eligibility criteria. Thirty full-text articles were assessed, and eight were excluded due to methodological weaknesses, lack of neurofeedback implementation, absence of anxiety-related outcomes, or insufficient electrophysiological information. Ultimately, 25 studies met all criteria and were included, representing a range of clinical and subclinical anxiety populations.

Neurofeedback interventions addressed multiple anxiety conditions. Five studies targeted Generalized Anxiety Disorder (GAD), eight focused on PTSD with co-occurring anxiety, and three examined Social Anxiety Disorder (SAD). The remaining studies explored test anxiety, chronic stress–related anxiety, mixed anxiety profiles, or secondary anxiety symptoms in other disorders. Several trials included individuals with moderate to severe or treatment-resistant symptoms (Nicholson et al., 2023; Scheinost et al., 2021), underscoring the clinical relevance of the observed improvements.

Neurofeedback modalities varied considerably. EEG-based approaches included alpha–theta training (Panisch & Hai, 2022), SMR enhancement (Wang et al., 2023), beta–theta modulation (Tinius & Tinius, 2021), and individualized qEEG-guided protocols (Arns et al., 2023). Frontal alpha asymmetry training also appeared frequently, given its relevance to emotional regulation (Reiter et al., 2021). Some studies integrated complementary techniques such as HRV biofeedback (Ros et al., 2023), microcurrent stimulation (Lam et al., 2023), or mindfulness-assisted NF (Chen et al., 2021), reflecting the rise of multimodal designs.

Real-time fMRI neurofeedback (rtfMRI-NF) represented a smaller but methodologically robust subset of trials, targeting neural regions essential for anxiety regulation, including the amygdala, insula, and prefrontal-limbic networks (Nicholson et al., 2024; Scheinost et al., 2021). These protocols generally produced large effect sizes, often exceeding those reported for EEG-based NF, likely due to their ability to modulate deeper subcortical circuitry.

Most randomized controlled trials reported significant anxiety reduction using validated measures such as HAM-A, STAI, LSAS, and GAD-7. For example, one trial found substantial decreases in trait anxiety following alpha–theta NF combined with mindfulness (Chen et al., 2021), and another reported strong improvements in GAD-7 and STAI scores after amygdala downregulation with rtfMRI-NF (Nicholson et al., 2023). A further study similarly observed significant reductions in chronic stress–related anxiety through combined EEG and HRV feedback (Ros et al., 2023).

Findings from systematic reviews reinforce these results. One meta-analysis identified moderate pooled reductions in anxiety (Russo et al., 2022), and another systematic review reported comparable effects across neurofeedback trials for anxiety disorders (Tolin et al., 2021). These reviews suggest that neurofeedback produces reliable, though not excessively large, improvements across anxiety populations.

Methodological quality, assessed using the MMAT, ranged from moderate to high (Hong et al., 2018). Thirteen studies scored between 90% and 100%, reflecting strong randomization, baseline equivalence, complete outcome reporting, and high protocol fidelity. Ten studies scored 80%, largely due to limited blinding—an inherent challenge in NF research (Thibault et al., 2018). Only two studies displayed notable weaknesses such as modest samples or incomplete blinding.

A notable strength of the reviewed literature is the consistent integration of physiological or neural indicators alongside self-report measures. For instance, one systematic review showed that improved insula regulation during rtfMRI-NF corresponded with reduced anxiety (Zhang et al., 2025), while another trial observed significant insula modulation in high-trait anxiety (Kim et al., 2024). EEG-based studies similarly reported increases in alpha power, enhanced SMR amplitude, and improved coherence patterns linked with emotional stability and attentional regulation (Cheng et al., 2015; Klimesch, 2012). These converging findings support the neurobiological credibility of NF-induced changes.

Overall, the evidence indicates that neurofeedback—particularly SMR training, alpha–theta protocols, frontal asymmetry modulation, and rtfMRI-based approaches—shows substantial promise for reducing anxiety across diverse populations. Despite methodological heterogeneity, the consistent positive outcomes highlight NF's potential as an effective adjunct or alternative to conventional anxiety treatments.

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4. Discussion and Conclusion

The findings of the present systematic review provide converging evidence that neurofeedback represents a promising and increasingly evidence-supported intervention for the reduction of anxiety symptoms across diverse clinical and subclinical populations. Across the included studies, both EEG-based and real-time fMRI neurofeedback protocols demonstrated consistent improvements in anxiety severity, emotional regulation, and cognitive functioning. The magnitude and consistency of these outcomes align with contemporary meta-analytic findings indicating moderate to large pooled effects of neurofeedback interventions for anxiety-spectrum disorders (Russo et al., 2022; Tolin et al., 2021). These results reinforce the conceptualization of anxiety as a disorder of dysfunctional neural regulation rather than solely maladaptive cognition or behavior, supporting interventions that directly target neural circuitry underlying emotional dysregulation.

One of the central findings emerging from this review is the effectiveness of EEG-based neurofeedback protocols, particularly sensorimotor rhythm (SMR), alpha enhancement, and alpha–theta training. Multiple randomized trials demonstrated significant reductions in generalized anxiety, social anxiety, test anxiety, and high-trait anxiety following EEG neurofeedback interventions (Liu et al., 2022; Mennella et al., 2020; Wang et al., 2023). These findings are theoretically consistent with electrophysiological models suggesting that anxiety is associated with excessive cortical arousal and instability in thalamocortical networks (Newson & Thiagarajan, 2019). SMR training appears to promote neural stability and attentional regulation, which indirectly reduces hypervigilance and physiological tension characteristic of anxiety disorders. Similar improvements observed in earlier clinical trials further support the capacity of SMR-based neurofeedback to modulate anxiety-related attentional dysregulation (Wang et al., 2019).

Alpha-based neurofeedback protocols also demonstrated strong therapeutic effects. Increased alpha activity has been linked to relaxation, efficient sensory inhibition, and reduced emotional reactivity (Klimesch, 2012). Trials targeting frontal alpha asymmetry showed notable symptom reduction in social anxiety, suggesting that balancing hemispheric activation may normalize approach–avoidance motivational systems disrupted in anxiety disorders (Bananejad et al., 2023; Harmon-Jones & Gable, 2018). Likewise, alpha–theta training has been associated with improvements in autonomic regulation and emotional processing, particularly among individuals with trauma-related anxiety (Imperatori et al., 2018; Young et al., 2022). The present findings closely mirror systematic reviews demonstrating that alpha-frequency neurofeedback enhances emotional regulation capacities central to anxiety reduction (Panisch & Hai, 2022; Reiter et al., 2021).

Importantly, individualized and comparative neurofeedback protocols showed that different frequency targets may yield distinct therapeutic profiles. Clinical trials comparing SMR and alpha–theta protocols found improvements across both conditions, with alpha–theta training producing greater reductions in state anxiety and emotional distress (Lotfinia et al., 2025). This observation supports emerging personalized medicine perspectives suggesting that optimal neurofeedback outcomes depend on baseline neurophysiological patterns and symptom characteristics rather than a single universal protocol (Arns et al., 2023). Individualized qEEG-guided neurofeedback has similarly demonstrated sustained symptom improvement, indicating that tailoring training parameters to individual neural signatures may enhance clinical effectiveness (Abdian et al., 2021).

Another important outcome of this review concerns the growing role of real-time fMRI neurofeedback. Studies targeting deep neural structures—including the amygdala, insula, and prefrontal-limbic connectivity networks—reported some of the largest treatment effects observed across the literature (Nicholson et al., 2022, 2023, 2024). Anxiety disorders are strongly associated with hyperactivation of limbic threat-processing regions alongside reduced prefrontal regulatory control (Arnsten, 2009; Drevets et al., 2008). By enabling participants to directly modulate these networks, fMRI-based neurofeedback appears to restore functional connectivity underlying adaptive emotion regulation. Comparable improvements following insula-targeted neurofeedback further support the importance of interoceptive awareness and salience processing in anxiety symptom reduction (Kim et al., 2024). Recent systematic reviews confirm that real-time neurofeedback targeting emotion-regulation circuits produces reliable improvements across anxiety and depressive conditions (Zhang et al., 2025).

The observed therapeutic benefits extend beyond symptom reduction to cognitive and behavioral outcomes. Several studies reported improvements in attention, working memory, inhibitory control, and emotional resilience following neurofeedback training. These findings align with

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cognitive neuroscience models emphasizing working memory and attentional control as central mechanisms in anxiety regulation (Cowan, 2021). Earlier neurofeedback research demonstrated enhancements in cognitive performance and intelligence measures, supporting the idea that neural efficiency increases with training (Angelakis et al., 2007; Jaušovec & Jaušovec, 2012). Improvements in task performance and emotional stability may therefore represent downstream effects of strengthened neural oscillatory coordination (Mikicin, 2015). Neuroplastic changes observed in structural neuroimaging studies further support this interpretation, indicating that neurofeedback induces measurable alterations in brain structure and connectivity (Ghaziri et al., 2013).

The results also highlight the effectiveness of multimodal and integrative neurofeedback interventions. Combining neurofeedback with cognitive behavioral therapy, mindfulness training, or heart rate variability biofeedback produced enhanced therapeutic outcomes compared with standalone interventions (Lam et al., 2023; Ros et al., 2023). These findings are consistent with broader psychological theories suggesting that neurobiological regulation and cognitive restructuring operate synergistically during treatment. Mindfulness-related mechanisms, including sustained attention and nonjudgmental awareness, appear to complement neurofeedback learning processes (Williams, 2019). Such integrative approaches may facilitate both top-down cognitive change and bottom-up neural regulation, thereby maximizing treatment effectiveness.

Meta-analytic and systematic evidence included in the review further reinforces neurofeedback's clinical relevance. Large pooled effect sizes have been reported for anxiety-spectrum disorders and trauma-related conditions (Askovic et al., 2023; Russo et al., 2022; Voigt et al., 2024). These outcomes suggest that neurofeedback may function as an effective adjunctive or alternative intervention, particularly for individuals who do not respond adequately to pharmacological or psychotherapeutic treatments. Neurofeedback has also demonstrated benefits when combined with medication in complex psychiatric populations, supporting its role within multimodal treatment frameworks (Li et al., 2024).

Despite encouraging outcomes, variability across studies remains an important consideration. Differences in electrode placement, training duration, feedback modality, and participant characteristics contributed to heterogeneous findings, a challenge frequently highlighted in neurofeedback research (Tolin et al., 2021). Some studies reported limited or null cognitive improvements, suggesting that neurofeedback effectiveness may depend heavily on training intensity, participant engagement, or protocol specificity (Mirifar et al., 2021). Furthermore, the possibility of expectancy or placebo effects continues to generate debate within the field. Critics argue that perceived improvements may partly reflect nonspecific therapeutic factors, emphasizing the need for rigorous sham-controlled designs (Thibault et al., 2018). Nevertheless, physiological changes observed in EEG biomarkers and functional connectivity patterns provide objective evidence supporting genuine neurobiological effects beyond placebo mechanisms (Wynn et al., 2020).

Another significant finding concerns accessibility and technological innovation. Traditional neurofeedback requires specialized clinical equipment and trained professionals, limiting widespread implementation. However, recent trials of home-based neurofeedback systems demonstrate comparable symptom improvements, suggesting that remote delivery may expand access to treatment (Hou et al., 2024). Systematic evaluations indicate acceptable adherence and usability, although concerns regarding supervision and signal reliability remain (Micoulaud-Franchi et al., 2024). Advances in portable neurotechnology may therefore play a critical role in future dissemination of neurofeedback interventions.

From a methodological perspective, the studies included in this review generally demonstrated moderate to high quality. Adoption of standardized reporting frameworks such as PRISMA enhanced transparency and reproducibility across systematic investigations (Page et al., 2021). Quality appraisal instruments such as AMSTAR-2 and MMAT contributed to improved evaluation of evidence reliability (Hong et al., 2018; Shea et al., 2017). The increasing methodological rigor observed in recent neurofeedback research suggests maturation of the field and growing alignment with evidence-based clinical standards.

Overall, the present findings support neurofeedback as a biologically grounded intervention capable of modifying neural circuits implicated in anxiety. By training self-regulation of brain activity, neurofeedback addresses core mechanisms underlying emotional dysregulation rather than solely treating symptomatic manifestations. Consistent reductions in anxiety severity across EEG and fMRI modalities indicate that neurofeedback may represent an important component of future personalized mental health care. Nevertheless, continued research is required to refine

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protocols, clarify mechanisms, and establish standardized clinical guidelines.

Several limitations should be considered when interpreting the findings of this review. First, considerable heterogeneity existed among included studies regarding neurofeedback protocols, session numbers, feedback modalities, and participant characteristics, which limited direct comparability and prevented quantitative synthesis. Second, many trials included relatively small sample sizes, potentially reducing statistical power and generalizability of results. Third, blinding procedures were often difficult to implement due to the interactive nature of neurofeedback training, raising the possibility of expectancy effects. Fourth, long-term follow-up assessments were limited in many studies, making it difficult to determine the durability of treatment gains. Finally, variations in outcome measures and reporting standards complicated evaluation of clinical effectiveness across studies.

Future research should prioritize large-scale randomized controlled trials with standardized neurofeedback protocols to enhance comparability across investigations. Studies examining long-term follow-up outcomes are essential to determine whether neurofeedback produces enduring neural and psychological changes. Further investigation into individualized treatment approaches based on baseline neural biomarkers may help identify predictors of treatment response and optimize protocol selection. Comparative trials evaluating neurofeedback against established treatments such as cognitive behavioral therapy or pharmacotherapy would clarify relative effectiveness. Additionally, research exploring neural mechanisms through multimodal neuroimaging and computational modeling could deepen understanding of how neurofeedback modifies emotion-regulation networks.

From a clinical perspective, neurofeedback may be considered a valuable adjunctive intervention for individuals with anxiety symptoms, particularly those who do not respond adequately to conventional treatments or who prefer non-pharmacological approaches. Clinicians should emphasize structured training protocols, adequate session frequency, and patient education regarding the learning-based nature of neurofeedback. Integration of neurofeedback with psychological therapies and lifestyle interventions may enhance therapeutic outcomes. Expanding access through supervised home-based systems could increase treatment availability while maintaining clinical oversight. Finally, interdisciplinary collaboration between clinicians, neuroscientists, and technology developers will be essential for translating neurofeedback research into routine mental health practice.

Authors' Contributions

All authors significantly contributed to this study.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

In this study, to observe ethical considerations, participants were informed about the goals and importance of the research before the start of the study and participated in the research with informed consent.

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