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Neurofeedback training for executive function in ADHD children: a systematic review and meta-analysis

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Executive function deficits are commonly observed in children diagnosed with attention deficit hyperactivity disorder (ADHD). This research investigates the effectiveness of neurofeedback training (NFT) in improving executive functions among this group. Studies were meticulously selected following stringent inclusion and exclusion criteria. The quality of these studies was assessed using the PEDro scale. Seventeen RCT studies were identified, totaling 939 participants. We observed significant improvements in global executive function ($p < 0.055$), inhibitory control ($p < 0.0001$) and working memory ($p < 0.05$) following NFT. Notably, NFT exceeding 1,260 min was more effective in enhancing inhibitory control ($p < 0.01$) and working memory ($p < 0.01$). Additionally, the effects of NFT on inhibitory control ($p = 0.05$) and working memory ($p < 0.01$) were found to be enduring. NFT is an effective intervention for improving inhibitory control and working memory in children with ADHD. Working memory exhibits a more significant enhancement when the duration exceeds 1260 min, while inhibitory control follows closely behind. Moreover, it has a more sustained effect on working memory, alongside a notable albeit secondary effect on inhibitory control.

Keywords Neurofeedback training, Executive function, ADHD, Children, Meta-analysis

ADHD, which is one of the most common mental disorders in children, is defined by attention challenges, heightened activity levels, and impulsivity. It affects about 10% of children worldwide[1,2]. And approximately half of the children diagnosed with ADHD exhibit impaired executive function (EF), which is a significant characteristic of the condition as indicated by research findings[3–5].

Executive function, a higher-order cognitive process, is integral to managing complex cognitive tasks and involves inhibitory control, working memory, and cognitive flexibility[6]. This capacity is pivotal for regulating diverse cognitive processes[7]. The developmental phase of executive function is crucial for children, influencing their academic performance[8,9], emotion regulation[10], and social functioning[11]. Furthermore, deficits in executive function correlate with a range of challenges including academic difficulties, behavioral problems, social struggles, and long-term psychological maladjustment[12]. This highlights the significance of implementing effective prevention and intervention strategies.

Pharmacological therapy, involving the use of amphetamines and methylphenidate, is a prevalent strategy for managing ADHD symptoms[13,14]. However, these treatments may induce side effects, including decreased appetite, sleep disturbances, nausea, and headaches. Additionally, prolonged use of pharmacological therapy could potentially result in stunted growth and cardiovascular risks[15–17]. Given these limitations, there is a critical need to explore non-invasive alternatives for effectively improving executive function in children with ADHD.

Neurological Techniques such as neurofeedback, transcranial stimulation, and hyperscanning are increasingly utilized in the treatment of children with neurodevelopmental disorders. Among these methods, neurofeedback has become the most widely adopted[18]. NFT is a noninvasive therapy designed to enhance brain function by monitoring and modifying brain electrical activity. In this process, participants receive instantaneous feedback on their brainwave patterns, enabling them to adjust and enhance specific brain regions based on this data[19]. By reviewing the existing researches, it was found that the number of studies on NFT and children has increased over time (Fig. 1A). The United Kingdom, Germany, the Netherlands, Iran, China, Switzerland, and Spain are

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pivotal contributors of NFT for children, making substantial advancements in this area (Fig. 1B). In particular, the number of research articles on neurofeedback training for children with ADHD ranked second (Fig. 1C). Children with ADHD often struggle with self-control. The goal of NFT is to enhance the brain's self-regulation in order to ameliorate and optimize individuals' cognition. Consequently, the current study aims to conduct an exhaustive review of the existing literature on the interplay between NFT and executive function in children with ADHD, hoping to provide valuable insights for future research.

Methods

This study strictly followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework for literature screening[20]. The protocol for the systematic review was registered with PROSPERO (CRD42024540735).

Search strategy

The literature review was performed across three databases: PubMed, EBSCO, and Web of Science. The search was restricted to English-language articles published from January 2000 to January 2024. To refine the search efficacy, a tactical mix of topic-specific and broad terms was utilized. Detailed below are the search terms employed: "neurofeedback" OR "brainwave biofeedback" OR "alpha feedback" OR "EEG Feedback" OR "electromyography feedback" OR "neurotherapy" OR "slow cortical potential" OR "SCP" OR "sensory motor rhythm" OR "SMR" AND "ADHD" OR "Attention Deficit Disorders with Hyperactivity" OR "Hyperkinetic Syndrome" AND "child" OR "children" OR "childhood" OR "pediatric" AND "cognition" OR "cognitive function" OR "cognitive ability" OR "cognitive performance" OR "executive function" OR "inhibition" OR "inhibitory control" OR "cognitive control" OR "working memory" OR "cognitive flexibility."

Inclusion criteria

(1) Participants: The study population comprised children and adolescents aged 6 to 18 years diagnosed with ADHD according to the criteria outlined in the Diagnostic and Statistical Manual of Mental Disorders (DSM) or the International Classification of Diseases (ICD). (2) Study Design: Included in the analysis were studies employing randomized or non-randomized controlled trials, as well as quasi-experimental designs. These studies were required to provide detailed statistical data including participant counts, means, standard deviations, and other pertinent information. (3) Types of Intervention: Types of Intervention: Neurofeedback has been implemented as one of the treatment interventions. Studies have compared NF to a control group or other interventions. (4) Variable: The primary independent variable under investigation is NFT. The dependent variables encompass cognitive functions, notably inhibitory control, working memory, and cognitive flexibility. (5) Outcome Measures: The included studies must utilize validated tools to assess executive function, such as neurocognitive tasks or questionnaires.

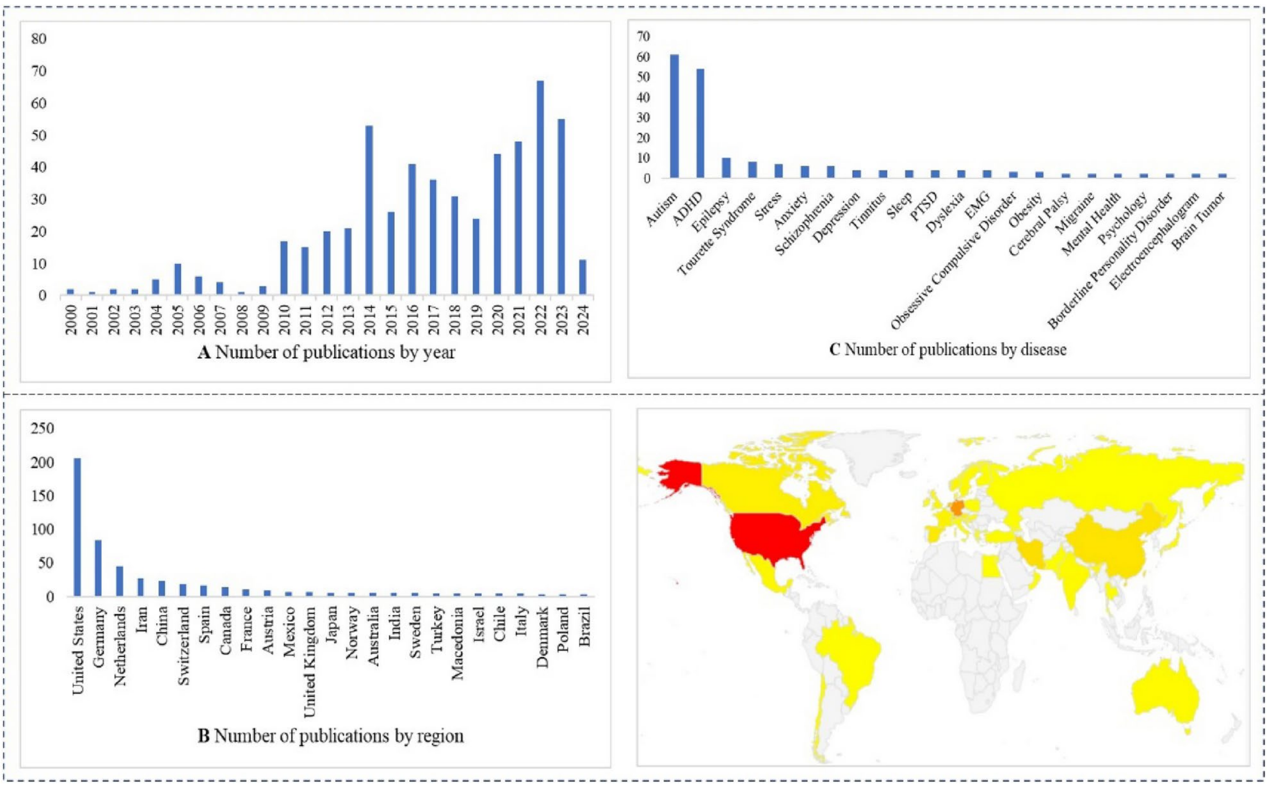

Fig. 1. Literature review.

Exclusion criteria

(1) Participants: The studies included mixed population samples of adults and children. (2) Study Design: Non-intervention studies, qualitative research, case studies, observational studies, review articles, conference abstracts, books, and other non-empirical literature forms were excluded. (3) Types of Intervention: The studies lack a control group or other comparative interventions.

Study selection and data extraction

Upon completing the literature search, the articles obtained were imported into NoteExpress for deduplication. Two researchers independently performed a preliminary screening of the articles based on their titles, abstracts, and keywords. Articles that passed this initial phase were then subjected to a more comprehensive review, which included a full-text examination. In instances of disagreement, a third researcher was consulted to achieve consensus on whether to include an article.

During the review process, both researchers systematically extracted essential information from each article, detailing the authors, country of publication, year of publication, and specifics regarding the study participants, such as number and age. Additionally, exhaustive details concerning the interventions (time, frequency, and duration), measurement tools employed, and the outcomes measured were meticulously recorded to ensure accuracy.

Quality assessment

The Physiotherapy Evidence Database (PEDro) scale is a validated and efficient instrument for assessing the methodological quality of research studies[21]. This scale includes 11 items that evaluate various aspects such as eligibility criteria, random allocation, concealment of allocation, baseline comparability, blinding of participants, therapists, and assessors, an attrition rate of $\leq 15\%$, implementation of intention-to-treat analysis, statistical comparisons between groups, and variability measurements. Each of items 2–11 is scored on a binary scale, where 1 point is given for criteria fulfillment and 0 points are assigned for non-fulfillment or ambiguous criteria. The total PEDro scale score is derived by summing these item scores, with interpretations as follows: scores below 4 denote poor quality, scores between 4 and 8 indicate good quality, and scores between 9 and 10 suggest high quality. The methodological quality of the included studies was independently assessed by two researchers using the PEDro criteria, with a third researcher consulted to resolve any disagreements.

Statistical analysis

Statistical analysis was performed using Review Manager 5.4 and Stata 12.0 software. For the meta-analysis, sample sizes, means, and standard deviations of both intervention and control groups were extracted pre- and post-intervention to compute the effect size. Considering the diversity in intervention durations and cognitive assessment methodologies, the *SMD* with a 95% *CI* was utilized as the aggregate effect size measure. The effect size was categorized as small (0.2–0.49), moderate (0.50–0.79), and large (≥ 0.8)[22]. Heterogeneity among the included studies was assessed using the Q-value and I^2 statistic. The Q-value, reflecting total variation, denotes significant heterogeneity if $p < 0.05$ and no significant heterogeneity if $p > 0.05$. I^2 quantifies the proportion of inter-study variance relative to total variance, with thresholds of 25%, 50%, and 75% indicating low, moderate, and high heterogeneity, respectively. A random effects model was applied in cases where $p < 0.05$ and $I^2 > 50\%$. In other scenarios, a fixed effects model was utilized[23]. And Egger's methods are applied to indicate significant publication bias for the analysis exploring association between risk of NFT and executive function.

Results

Search results

Initial searches identified 503 relevant articles. Following deduplication and the exclusion of irrelevant literature, 394 articles remained. Preliminary evaluation based on titles and abstracts further refined the pool to 101 articles. A detailed examination of the full texts ultimately led to the inclusion of 17 articles for analysis. The article selection process is depicted in Fig. 2.

Study selection and characteristics

The studies incorporated in this review included 17 randomized controlled trials involving a total of 939 participants aged 6 to 17 years, all diagnosed with ADHD. Of these, 477 participants (approximately 50.8%) underwent EEG or fMRI NFT, while 462 participants (approximately 49.2%) were assigned to control groups. The duration of NFT sessions varied, ranging from 2 to 25 weeks, with a frequency of one to seven sessions per week. Each session lasted from 8.5 to 60 min, resulting in a total NFT duration of 119 to 2400 min. Table 1 presents detailed information regarding the characteristics of the participants, frequency and duration of NFT, and the measurements from the included studies.

Risk of bias assessment

The PEDro scale scores for the included studies ranged from 6 to 10, with an average score of 7.76. Notably, no study scored below 5. Specifically, eleven studies fell within the 6 to 8 range, and six studies achieved scores between 9 and 10. All studies fulfilled the criteria for eligibility, random allocation, an attrition rate of $\leq 15\%$, intention-to-treat analysis, statistical comparison between groups, and reporting of point measures and variability. Sixteen studies reported baseline comparability, twelve incorporated allocation concealment, ten implemented blinding of participants, six involved blinding of therapists, and five applied blinding of assessors. These assessments indicate that the overall quality of the literature is generally high, as detailed in Table 2. The risk of bias assessments for the included studies were displayed in Figs. 3 and 4.

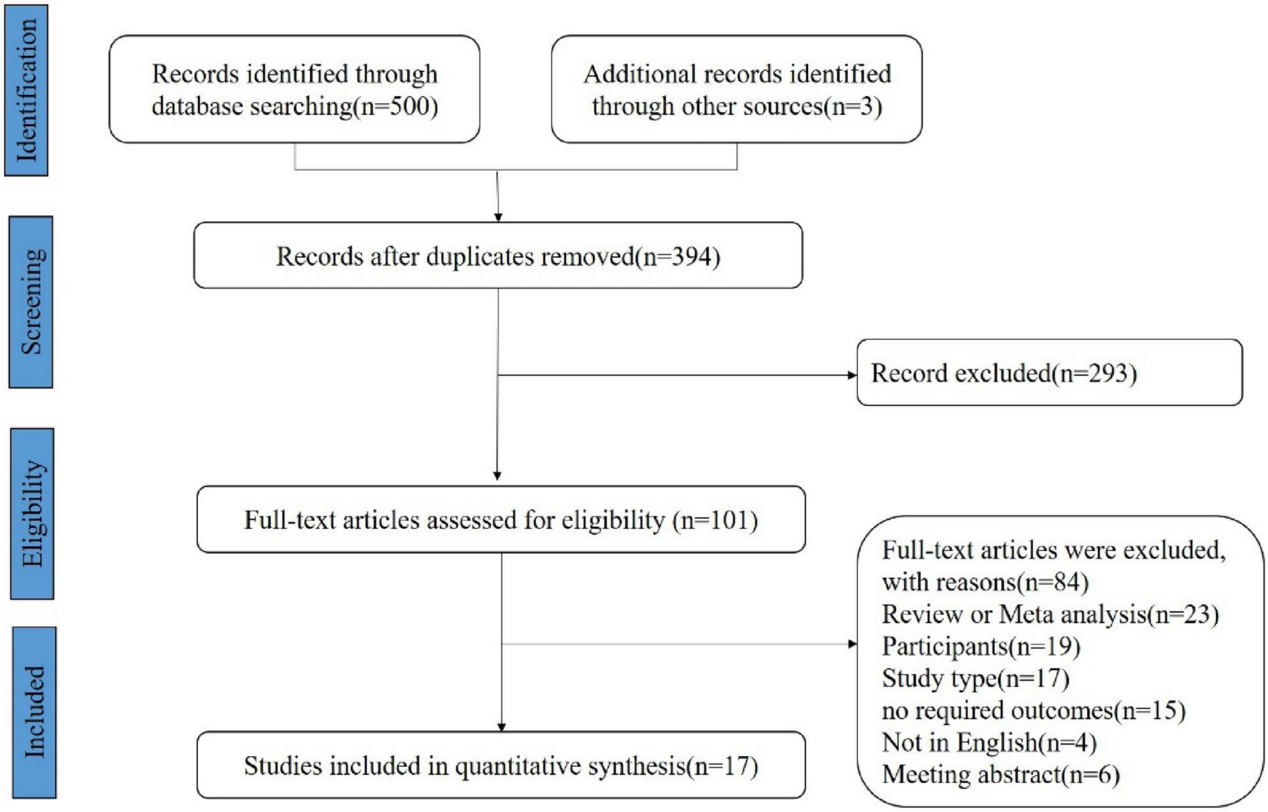

Fig. 2. PRISMA flowchart diagram of the selection process of studies.

Meta-analysis results

Effect of NFT on EF

In the analysis of the relationship between NFT and global executive function, three studies incorporating 1116 participants were evaluated. These studies displayed low statistical heterogeneity ($I^2 = 0\%$, $p > 0.05$), which justified the use of a fixed effects model. The findings revealed a significant positive impact of NFT on inhibitory control ($SMD = -0.44$, 95% $CI = -0.81$ to -0.07, $Z = 2.30$, $p < 0.05$) (Fig. 5A).In the analysis of the relationship between NFT and inhibitory control, twelve studies incorporating 640 participants were evaluated. These studies displayed low statistical heterogeneity ($I^2 = 26\%$, $p > 0.05$), which justified the use of a fixed effects model. The findings revealed a significant positive impact of NFT on inhibitory control ($SMD = 0.36$, 95% $CI = 0.18–0.53$, $Z = 4.04$, $p < 0.0001$) (Fig. 5B). In terms of working memory, seven studies involving 370 participants were examined. The results showed a beneficial effect of NFT on working memory ($SMD = 0.37$, 95% $CI = 0.01–0.74$, $Z = 2.01$, $p < 0.05$), with high heterogeneity observed ($I^2 = 65\%$, $p < 0.01$) (Fig. 5C).

Egger's regression test indicated no publication bias in studies related to global executive function, inhibitory control and working memory (all $p > 0.05$).

The dose–response effect of NFT on EF

This study utilized a subgroup comparison approach to evaluate the impact of different NFT durations on executive function among children diagnosed with ADHD. The duration of NFT sessions varied from 119 to 2400 min. Participants were divided into two groups based on the median duration of intervention: those receiving less than 1260 min of training were categorized as the short-term training group, while those with training durations exceeding 1260 min were classified as the long-term training group.

In the short-term training group, six studies involving 227 participants examined inhibitory control but found no significant difference between the neurofeedback and control groups ($SMD = 0.221$, 95% $CI = -0.06–0.48$, $Z = 1.53$, $p > 0.05$), with a low heterogeneity ($I^2 = 41\%$, $p > 0.05$) (Fig. 6A). Additionally, four studies with 190 participants focusing on working memory also reported no significant difference between the two groups ($SMD = 0.31$, 95% $CI = -0.33–0.95$, $Z = 0.96$, $p > 0.05$), while exhibiting high heterogeneity ($I^2 = 78\%$, $p < 0.05$) (Fig. 6B). Egger's regression test indicated no publication bias in the studies on inhibitory control($p > 0.05$) and working memory ($p > 0.05$) in the short-term neurofeedback group.

In the long-term training group, five studies with 280 participants focusing on inhibitory control revealed a significant difference between the NFT and control groups ($SMD = 0.30$, 95% $CI = 0.10–0.58$, $Z = 2.75$, $p < 0.01$), with low heterogeneity ($I^2 = 47\%$, $p > 0.05$) (Fig. 7A). Three studies with 180 participants focusing on working memory demonstrated a significant difference between the two groups ($SMD = 0.441$, 95% $CI = 0.12–0.71$, $Z = 2.72$, $p < 0.01$), also with low heterogeneity ($I^2 = 26\%$, $p > 0.05$) (Fig. 7B). The findings revealed that NFT had

Study	Region	Age (year)	Sample	Design	Intervention	Intervention time	ASD diagnostic criteria	Measure index	Measure task
Alegria[24] et al. (2017)	UK	12–17	EG: n = 18 ICG: n = 13	RCT	Real-time fMRI NFT (rIFG) VS. No intervention	2 weeks, 7 sessions/week, 8.5 min/session, total 119 min	DSM-5, K-SADS-PL	IC	GNG
Bakhsha-yesh[25] et al. (2011)	Italy	6–14	EG: n = 14 ACG: n = 14	RCT	EEG NFT (TBR) VS. EMG BF	10–15 weeks, 2/3 sessions/week, 30 min/session, total 900 min	ICD-10	IC	CPT
Beauregard[26] et al. (2006)	Canada	8–12	EG: n = 15 ICG: n = 5	RCT	EEG NFT (TBR) VS. No intervention	13.5 weeks, 3 sessions/week, 60 min/session, total 2400 min	DSM-5	IC	GNG
Bink[27] et al. (2014)	Netherlands	16	EG: n = 45 ACG: n = 26	RCT	EEG NFT (TBR) + TAU; VS. TAU	25 weeks, 2–3 sessions/week, 40 min/session, total 1200 min	DSM-5	WM; CF	DSB; TL
Dobrakowski[28] et al. (2020)	Poland	6–12	EG: n = 24 ICG: n = 24	RCT	EEG NFT (PAF) VS. No intervention	10 weeks, 1 session/week, 45 min/session, total 450 min	DSM-5, ICD-10	WM	N-back
Geladé[29] et al. (2017)	Netherlands	7–13	EG: n = 36 ACG: n = 37	RCT	EEG NFT (TBR) VS. PA	10–12 weeks, 3 sessions/week, 45 min/session, total 1350 min	DSM-5	IC, WM	SST, VSWM
Geladé[30] et al. (2018)	Netherlands	7–13	EG: n = 33 ACG: n = 31	RCT	EEG NFT (TBR) VS. PA	10–12 weeks, 3 sessions/week, 45 min/session, total 1350 min	DSM-5	IC, WM	SST, VSWM
Ging-Jehli[31] et al. (2023)	USA	7–10	EG: n = 55 ICG: n = 78	RCT	EEG NFT (TBR) VS. No intervention	not explicitly stated	DSM-5; AODS-2	IC	IVA2-CPT, GNG
Heinrich[32] et al. (2014)	Germany	7–14	EG: n = 13 ICG: n = 9	RCT	EEG NFT (SCP) VS. No intervention	7 weeks, 7 sessions/week, 50 min/session, total 1250 min	DSM-5; Diagnostic Checklist for ADHD	IC	CPT
Maurizio[33] et al. (2014)	Switzerland	8.5–13	EG: n = 12 ACG: n = 2	RCT	EEG NFT (SCP + TBR) VS. No EMG BF	12 weeks, 2–3 sessions/week, 30 min/session, total 1080 min	DSM-5	Global EF	BRIEF
Moradi[34] et al. (2022)	Iran	10.1	EG: n = 16 ICG: n = 16	RCT	EEG NFT (TBR) VS. No Intervention	3 months, 3 sessions/week, 15 min/session, total 1620 min	DSM-5	IC, WM	CPT, WWMT
Moreno-García[35] et al. (2019)	Spain	7–14	EG: n = 19 ACG1:n = 19 ACG2:n = 19	RCT	EEG NFT (TBR) VS BT or PH	20 weeks, 4 sessions/week, 24 min/session, total 40 session total 960 min	DSM-5; ADHD RS-IV	IC	CPT
Shereena[36] et al. (2019)	India	6–12	EG: n = 15 ICG: n = 15	RCT	EEG NFT (TBR) VS. No intervention	3.5–5 months, 3–4 sessions/week, 20–40 min/session, total 1200 min	ICD-10	IC, WM, CF	GNG, N-back, CTT
Steiner[37] et al. (2014)	Boston	7–11	EG: n = 34 ACG: n = 34 ICG: n = 36	RCT	EEG NFT (TBR) VS. CT/No intervention	5 months, 3 sessions/week, 45 min/session, total 1800 min	DSM-5	Global EF	BRIEF
Steiner[38] et al. (2011)	Boston	12.4	EG: n = 9 ICG: n = 13	RCT	EEG NFT (TBR) VS. No intervention	4 months, 2 sessions/week, 45 min/session, total 1440 min	DSM-5	Global EF	BRIEF
Continued									

Study	Region	Age (year)	Sample	Design	Intervention	Intervention time	ASD diagnostic criteria	Measure index	Measure task
Vollebregt[39] et al. (2014)	Netherlands	8–15	EG: n = 60 ICG: n = 60	RCT	EEG NFT (individualized: SMR, beta, theta) VS. No intervention	15 weeks, 2 sessions/week, 20 min/session, total 720 min	DSM-5	WM	Digit span WISC-III
Wangler[40] et al. (2011)	Germany	8–12	EG: n = 59 ACG: n = 35	RCT	EEG NFT (SCP + TBR) VS. Attention Training	9 weeks, 2–3 sessions/week, 50 min/session, total 1800 min	DSM-5	IC	ANT

Table 1. Characteristics of the included studies. EG: Experimental Group; ICG: inactive controls group; RCT: Randomized Controlled Trial; rIFG: right inferior prefrontal cortex; ST: standard treatment; DSM-5: Diagnostic and Statistical Manual of Mental Disorders, 5th edition; K-SADS-PL: Kiddie Schedule of Affective Disorders and Schizophrenia for School-Age Children-Present and Lifetime Version; IC: Inhibitory Control; GNG: Go/No-go; ACG: active control group; EMG BF: Electromyogram Biofeedback; ICD-10: International Classification of Diseases, Tenth Revision; CPT: Continuous Performance Task; TAU: Treatment As Usual; WM: Working Memory; CF: Cognitive Flexibility; DSB: Digit Span Backward; TL: Tower of London; PAF: peak alpha frequency; PA: Physical Activity; SST: Stop-signal Task; VSWM: Visual Spatial Working Memory Task; AODS-2: Autism Diagnostic Observation Schedule, Second Edition; IVA2-CPT: Integrated Visual and Auditory Continuous Performance Test; EF: Executive Function; BRIEF: Behavior Rating Inventory of Executive Function; WWMT: Wechsler Working Memory Test; BT: Behavior Therapy; PH: Pharmacology; ADHD RS-IV: ADHD Rating Scale–IV; CTT: Color Trails Test; CT: cognitive training; WISC-III: Wechsler Intelligence Scale for Children, Three Edition; SMR: sensory motor rhythm; ANT: Attention Network Test.

Study	EC	RA	CA	CB	BP	BT	BA	AT ≤ 15%	IITA	SCBG	MV	Total score
Alegria[24] et al. (2017)	1	1	1	1	1	0	0	1	1	1	1	8
Bakhshayesh[25] et al. (2011)	1	1	0	1	1	0	0	1	1	1	1	7
Beauregard[26] et al. (2006)	1	1	1	1	0	0	0	1	1	1	1	7
Bink[27] et al. (2014)	1	1	1	1	0	0	0	1	1	1	1	7
Dobrakowski[28] et al. (2020)	1	1	0	1	0	0	0	1	1	1	1	6
Geladé[29] et al. (2017)	1	1	1	1	1	1	0	1	1	1	1	9
Geladé[30] et al. (2018)	1	1	1	1	1	1	0	0	1	1	1	8
Ging-Jehli[31] et al. (2023)	1	1	0	1	1	1	1	1	1	1	1	9
Heinrich[32] et al. (2004)	1	1	1	1	1	0	0	1	1	1	1	8
Maurizio[33] et al. (2014)	1	1	1	0	1	1	1	1	1	1	1	9
Moradi[34] et al. (2022)	1	1	1	1	1	0	1	1	1	1	1	9
Moreno-García[35] et al. (2019)	1	1	0	1	0	0	0	1	1	1	1	6
Shereena[36] et al. (2019)	1	1	0	1	0	0	0	1	1	1	1	6
Steiner[37] et al. (2014)	1	1	1	1	1	1	1	1	1	1	1	10
Steiner[38] et al. (2011)	1	1	0	1	0	0	0	1	1	1	1	6
Vollebregt[39] et al. (2014)	1	1	1	1	1	1	1	1	1	1	1	10
Wangler[40] et al. (2011)	1	1	1	1	0	0	0	1	1	1	1	7

Table 2. Methodological quality of the included studies. EC: Eligibility criteria; RA: Random allocation; CA: concealment of allocation; CB: comparability at baseline; BP: blinding of participants; BT: blinding of therapists; BA: blinding of assessors; AT ≤ 15%: attrition rate ≤ 15%; IITA: implementation of intention-to-treat analysis; SCBG: statistical comparison between groups; MV: measures of variability.

a significant positive impact on inhibitory control and working memory when participants underwent NFT for more than 1260 min. Egger's regression test applied to the long-term neurofeedback group revealed a publication bias was detected in the studies on inhibitory control ($p = 0.012 < 0.05$) and working memory ($p = 0.027 < 0.05$).

The sustained effects of NFT on EF (6 to 12 months)

This study assessed the long-term effects of NFT on executive function, particularly focusing on the sustained impacts observable 6 to 12 months after the training. In the realm of inhibitory control, two studies highlighted a marginally significant difference between the NFT and control groups ($SMD = 0.35$, 95% $CI = 0.00–0.69$, $Z = 1.96$, $p = 0.05$), with no heterogeneity detected ($I^2 = 0\%$, $p > 0.05$) (Fig. 8A). Regarding working memory, three studies demonstrated a significant difference between the two groups ($SMD = 0.63$, 95% $CI = 0.19–1.07$, $Z = 2.79$, $p < 0.01$), though with high heterogeneity ($I^2 = 53\%$, $p > 0.05$) (Fig. 8B). Given the limited number of studies (only two) focusing on inhibitory control, publication bias testing was not conducted for this specific subset.

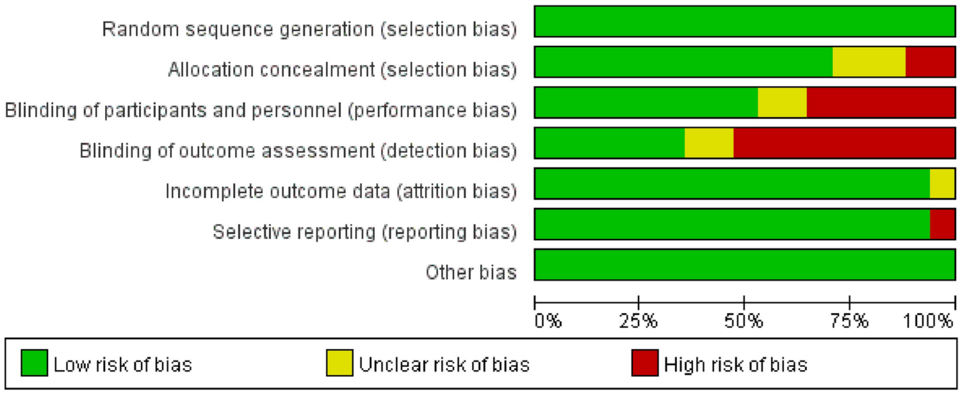

Fig. 3. Risk of bias graph of all included study.

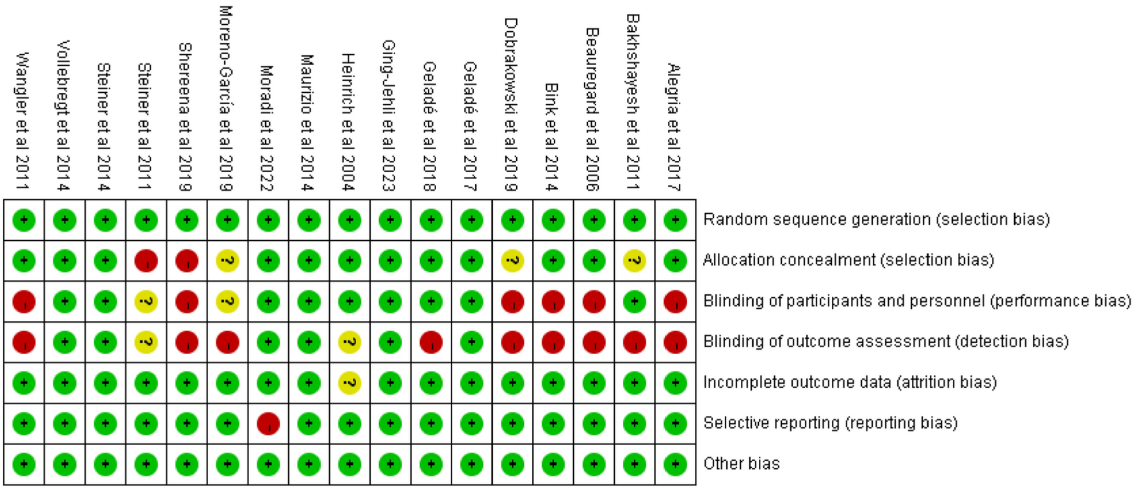

Fig. 4. Risk of bias summary of all included study.

However, Egger's regression test applied to the studies on working memory revealed no evidence of publication bias ($p > 0.05$).

Discussion

This study primarily focused on analyzing inhibitory control and working memory due to the limited research available on the relationship between NFT and cognitive flexibility. The findings of the meta-analysis indicated that NFT exerted a medium effect on both inhibitory control and working memory in children with ADHD. These results are consistent with those reported in several other meta-analyses[41–43].However, these findings are subject to debate. A particular meta-analysis reported no significant improvement in executive function in children with ADHD following neurofeedback[44]. This outcome was associated with several contributing factors identified in the study. Firstly, the inclusion of only six studies raises concerns regarding potential bias and the limited sample size, underscoring the scarcity of randomized controlled trials (RCTs) in this area. Secondly, variations in the design of interventions, including the frequency and duration of the interventions, could have influenced the aggregated results[45]. Therefore, more comprehensive research is needed to fully explore the effects of NFT on inhibitory control and working memory, as well as to control for non-specific effects.

The results of the meta-analysis on neurofeedback and working memory in children with ADHD revealed considerable heterogeneity across studies, which is closely associated with variations in neurofeedback protocols. This analysis included three NFT protocols: TBR (5 studies), PAF(1 study), and personalized (1 study). The studies included predominantly used TBR neurofeedback training, which may be the most effective protocol. However, this conclusion needs to be validated by future research. In addition, the heterogeneity between neurofeedback and working memory studies may be related to the cognitive task paradigms. There are five cognitive task paradigms: DSB (1 study), N-back (2 studies), VSWM (2 studies), WMMT (2 studies), and DS-WISC-III (1 study). Given the potential influence of different neurofeedback protocols and cognitive task paradigms on the results, caution is warranted when interpreting the effects of NFT on working memory in children with ADHD. Due to the significant disparity in the number of studies across the various protocols and cognitive task paradigams, a detailed subgroup analysis was not conducted. Future meta-analyses should adopt

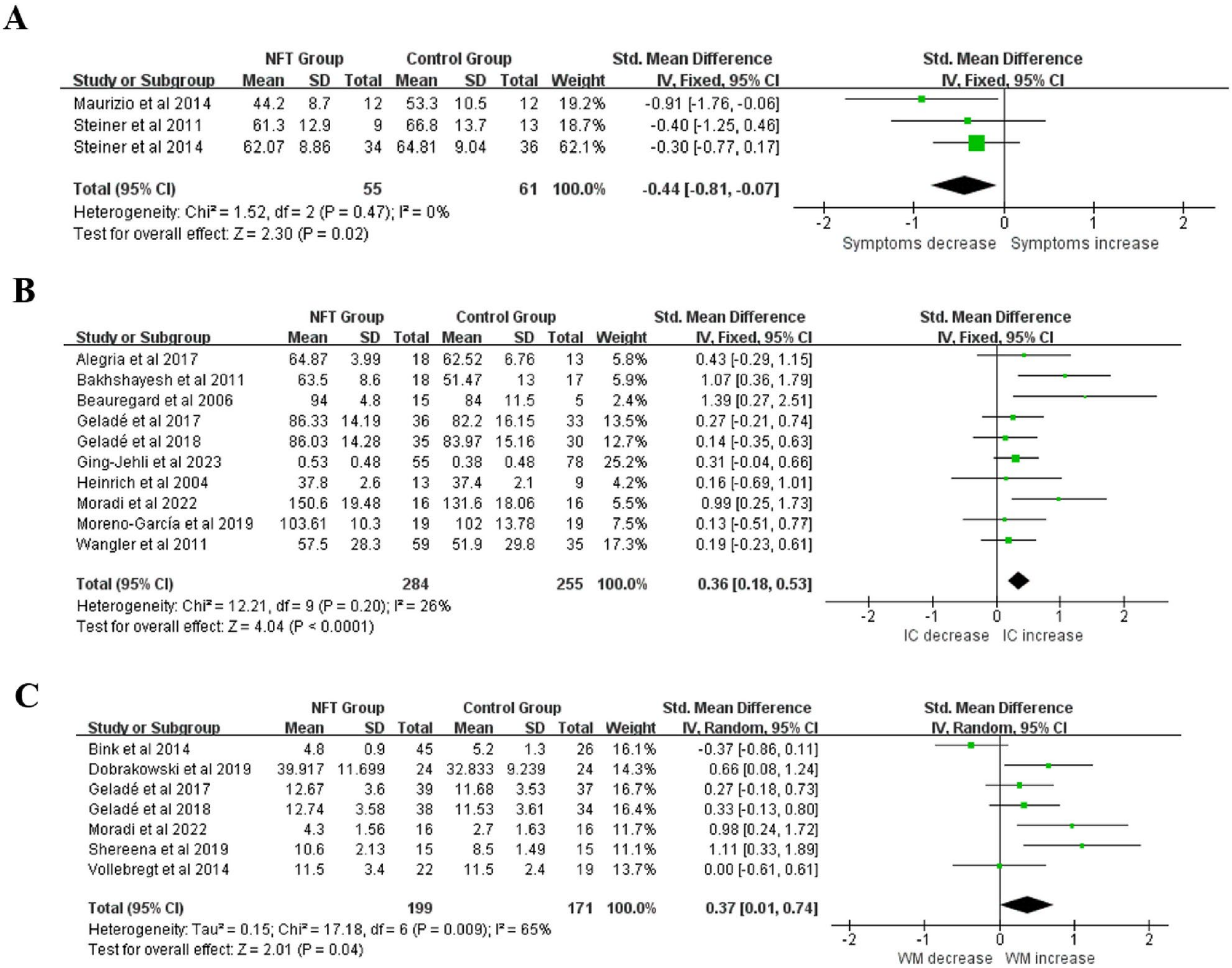

Fig. 5. Pairwise meta-analysis. NFT effects on global executive function (**A**), inhibitory control (**B**), and working memory (**C**) by comparison group type (experimental group vs. control group). SD = Standard Deviation; Std Mean Difference = Standardized Mean Difference; Random = Random Effects Model; Fix = Fix Effects Model; IV = Inverse Variance (a method of weight allocation); CI = Confidence Interval; I^2 = Higgins' I^2; ◆ = Overall effect estimates from all studies pooled together in this meta-analysis. If ◆ cross the line signifies no difference between groups (the same below).

stricter inclusion criteria and perform subgroup analyses to more clearly elucidate the specific effects of different neurofeedback protocols on working memory in children with ADHD.

The effectiveness of NFT in enhancing inhibitory control and working memory appears to be contingent on the duration of the training. Presently, there is no established consensus regarding the optimal duration for such training. The current study was divided into short-term NFT group and long-term NFT group according to the median intervention time. We found that short-term NFT training lasting less than 1260 min did not show a notable impact on inhibitory control and working memory. High heterogeneity is noted in short-term NFT on working memory. This heterogeneity may be attributed to variations in NFT protocols, including different frequencies and durations; and individual differences among ADHD children, such as age, symptom severity, and comorbidities. Additionally, the diversity in paradigms employed for cognitive task assessments may have contributed to this bias[46]. Given the complexity of cognitive structures, different cognitive paradigms may lead to variability in research outcomes. Therefore, future studies should aim to use a variety of cognitive measurement tools to comprehensively assess a broad range of cognitive components, in order to reduce the confounding effects of task-specific influences on the results.

While NFT training time exceeding this threshold (1260 min) demonstrates a small to moderate effect. However, it should be acknowledged that there is a publication bias in favor of the results of successful long-term neurofeedback training, potentially attributed to the limited number of studies included. Future studies should aim to increase sample sizes to enhance statistical power, refine experimental designs to minimize potential biases, and implement more rigorous control measures to better account for confounding variables. By carefully addressing these factors, future studies can strengthen the robustness and reliability of their conclusions, ultimately contributing to a clearer understanding of the effectiveness of NFT for ADHD.

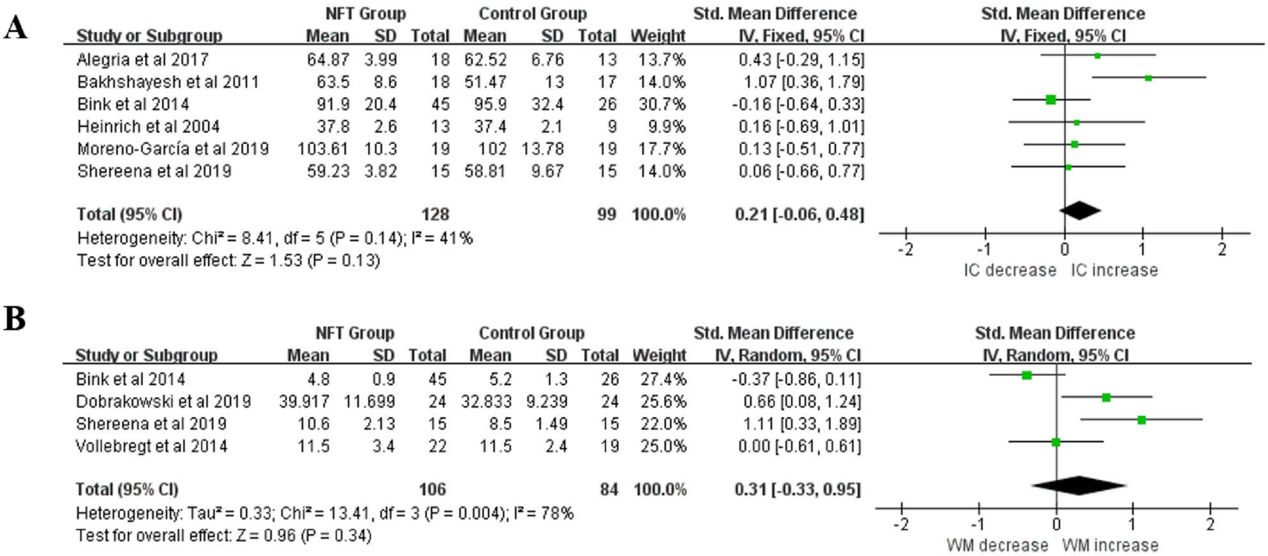

Fig. 6. Pairwise meta-analysis. Short-term NFT effects on inhibitory control (**A**) and working memory (**B**) by comparison group type (experimental group vs. control group).

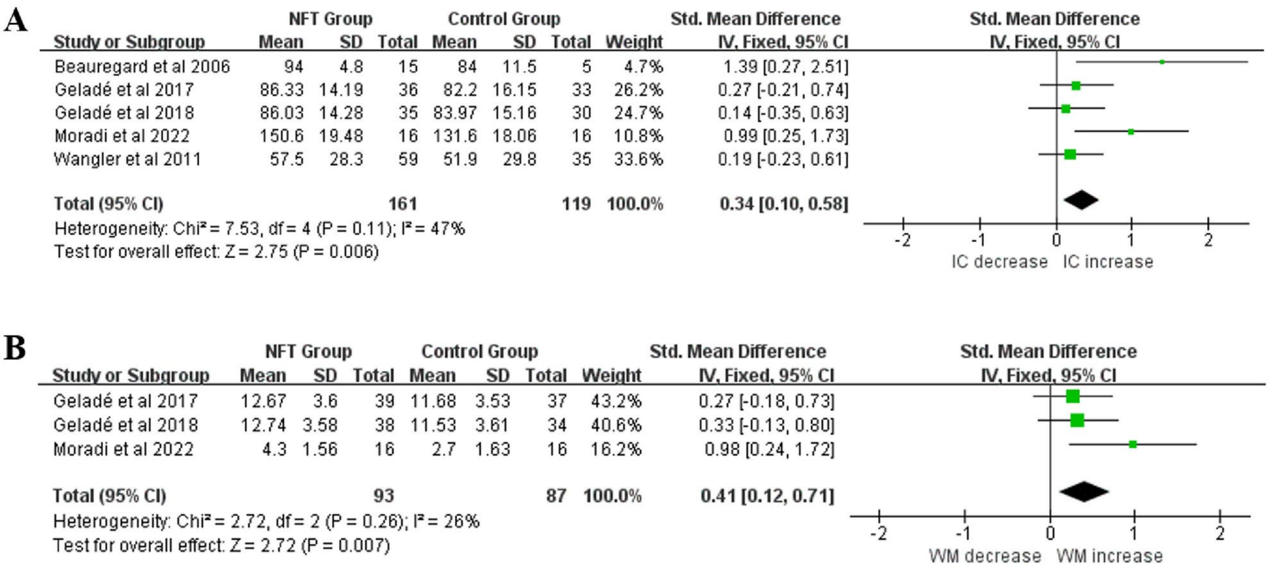

Fig. 7. Pairwise meta-analysis. Long-term NFT effects on inhibitory control (**A**) and working memory (**B**) by comparison group type (experimental group vs. control group).

This study further indicates that NFT has a medium to large, sustained effect on inhibitory control and working memory. Notably, the enhancement in executive functioning is sustained for at least 6–12 months post-training. This result is similar to the effect of NFT on attention and impulsivity in children with ADHD. Compared to no NFT control treatments, NFT appears to have more durable treatment effects on attentional and impulsivity reduction, for at least 6 months following treatment[47]. In addition, this study also found the enduring impact on working memory is more marked than on inhibitory control. This disparity may be related to the specific challenges faced by children with ADHD, who often struggle with control abilities. While NFT improves inhibitory control, achieving significant progress necessitates a long-term commitment[48]. Consequently, emphasizing the importance of focusing on inhibitory control in the daily management of ADHD in children is essential.

NFT incorporates a variety of protocols, each underpinned by distinct neurophysiological mechanisms, to improve executive function. A prevalent method for addressing ADHD is Theta-beta ratio (TBR) NFT, based on the Quantitative Electroencephalography (QEEG) protocol. In TBR neurofeedback, the upregulation of theta frequencies has been specifically linked to an increase in P3 amplitude in No-go tasks[49]. Protocols that involve training in beta upregulation or a combination of both theta and beta frequencies resulted in less specific effects.

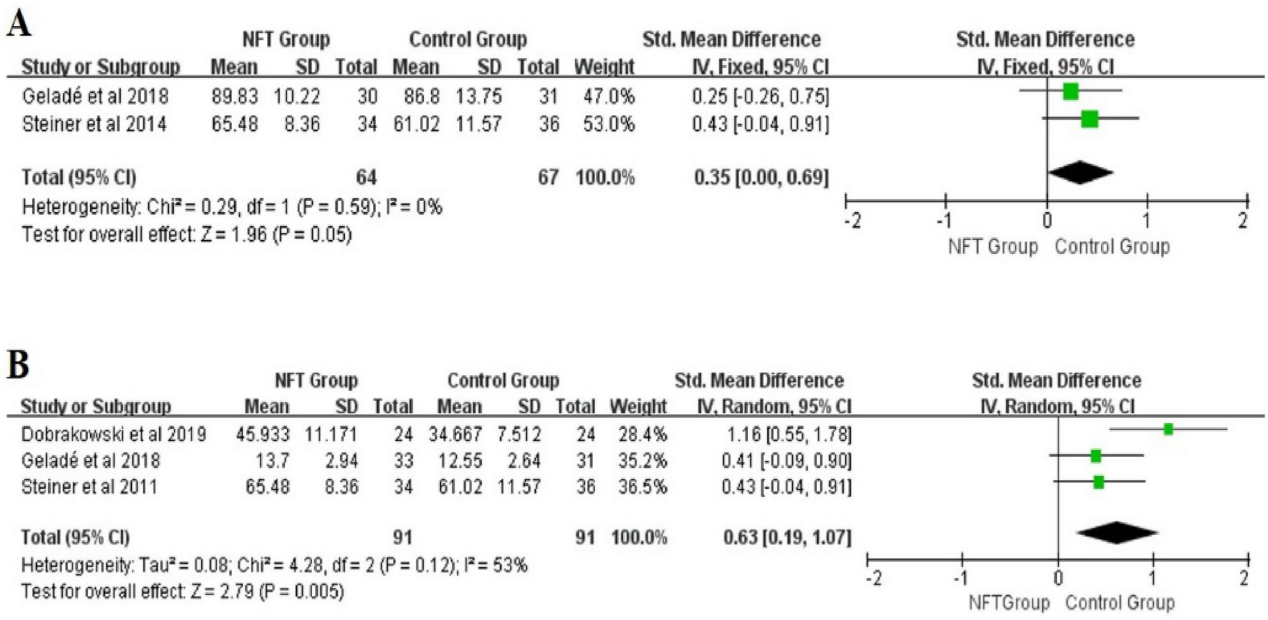

Fig. 8. Pairwise meta-analysis. sustained effects of NFT on inhibitory control (**A**) and working memory (**B**) by comparison group type (experimental group vs. control group).

On the other hand, focusing exclusively on enhancing beta frequencies during NFT, without concurrent theta frequency regulation, consistently improved both response inhibition and conflict control[50]. Another method, slow cortical potentials (SCP) NFT, employs the Event-Related Potentials (ERP) protocol. Research indicates that SCP training, following neurofeedback sessions, contributes to an increase in the contingent negative variation (CNV), a change specifically attributed to this type of training[40]. SCP neurofeedback is designed to enhance negative cortical potentials in the somatosensory motor cortex, which improves attention resource allocation and ultimately enhances cortical regulatory functions in individuals with ADHD. A critical aspect of NFT is its ability to enhance brain neuroplasticity—the capacity of the brain to adapt and reorganize. This enhancement significantly contributes to improvements in executive functions. Future research should focus on optimizing and personalizing NFT protocols based on individual neurophysiological profiles to maximize enhancements in executive functions.

NFT is increasingly acknowledged as a non-pharmacological adjunctive approach to augment executive function in children diagnosed with ADHD. It is crucial to recognize neurofeedback as a complementary therapy rather than a standalone treatment. Its effectiveness can be considerably enhanced when integrated with other therapeutic strategies, such as cognitive therapy[51] and cognitive-behavioral therapy (CBT). Research indicates that combining NFT with cognitive therapy yields more comprehensive improvements in executive functions. Specifically, cognitive training effectively enhances inhibitory control, whereas NFT demonstrates significant improvements in working memory[52]. The amalgamation of NFT with CBT has been extensively validated in numerous studies as significantly beneficial for improving the executive function of children with ADHD[53–55]. Additionally, integrating pharmacotherapy with NFT can be an effective complementary treatment strategy. Although NFT alone has shown a superior effect on executive function compared to medication[56], the combination of both NFT and medication has proven more effective in reducing ADHD symptoms and enhancing executive functioning[57].

In light of these findings, it is imperative for clinicians and researchers to embrace a diversified and pragmatic treatment approach for children with ADHD. This strategy should ideally integrate NFT, medication therapy, and cognitive behavioral therap[58]. This comprehensive treatment model is designed to achieve superior therapeutic outcomes and is actively endorsed at an international level[59].

Conclusion

NFT is an effective intervention for improving executive function in children with ADHD, specifically inhibitory control and working memory. This approach demonstrates a more pronounced impact on working memory when extended beyond 1000 min, with inhibitory control following closely behind. Furthermore, the evidence suggests that NFT may have sustained effects on both working memory and inhibitory control. Given the relatively small number of studies assessing long-term effects and the potential for publication bias, further research is necessary to confirm these effects and to better understand the mechanisms underlying NFT's impact on executive functions in children with ADHD.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Xiaoke Zhong, Xiaoxia Yuan, and Changhao Jiang wrote the main manuscript text. Xiaoke Zhong and Yuanfu Dai prepared figures. All authors reviewed the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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