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ORIGINAL ARTICLE

The Effects of Theta/Beta-based Neurofeedback Training on Attention in Children with Attention Deficit Hyperactivity Disorder: A Systematic Review and Meta-analysis

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Abstract

Neurofeedback training is a common treatment option for attention deficit hyperactivity disorder (ADHD). Given theta/beta-based neurofeedback (T/B NF) training targets at the electrophysiological characteristics of children with ADHD, benefits for attention may be expected. PsycINFO, PubMed, ScienceDirect, Scopus, and Web of Science were searched through December 31, 2020. Studies were evaluated with Risk of Bias tools. Within-group effects based on Pre- and Post-treatment comparisons of the Intervention Group, and Between-group effects based on the between-group differences from Pre-treatment to Post-treatment were calculated. Nineteen studies met selection criteria for systematic review, 12 of them were included in meta-analysis. Within-group effects were medium at Post-treatment and large at Follow-up. Between-group analyses revealed that T/B NF was superior to waitlist control and physical activities, but not stimulant medication. Results showed that T/B NF has benefits for attention in children with ADHD, however, cautions should be taken when interpreting the findings.

Keywords ADHD · Neurofeedback · Theta/beta-based neurofeedback · Attention problems · Children

Introduction

Attention deficit hyperactivity disorder (ADHD) is a common neurodevelopmental disorder in children [1, 2]. The worldwide prevalence is approximately 5% [3] and about 65% of children with ADHD have symptoms that persist into adulthood [4]. The core characteristics of ADHD are inattention and/or hyperactivity/impulsivity [5]. Due to attention problems and impulsive behaviours, children with ADHD may have lower academic achievement, poorer social relationships, and lower quality of life than children without ADHD [6, 7].

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Management of ADHD-Related Attention Problems

Pharmacological Intervention

Management of the attention problems in children with ADHD includes both pharmacological and non-pharmacological approaches [1]. The benefits of stimulant medications for attention problems in children with ADHD have been well-established [8–10]. However, there is also a list of side effects of psychostimulants such as headache, lack of appetite, insomnia, stunted growth, mood changes, suicidal thoughts, violent behaviours and other problems [11]. This plethora of side effects may make parents hesitate to choose medication as the first line treatment for their children with ADHD, and non-pharmacological interventions become preferred options [12].

Non-pharmacological Intervention

Evidence demonstrates that some non-pharmacological interventions have benefits for attention problems in children with ADHD, such as cognitive/executive functions training [13], behavioural management intervention [14],

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cognitive-behavioural therapy (CBT) [15], and neurofeedback (NF) training [16]. Among these treatments, NF training has received growing interest in recent years.

Neurofeedback (NF)

Neurofeedback (NF) is a kind of biofeedback, there are five EEG-related types of NF: (i) Low-energy neurofeedback system (LENS), which delivers a weak electromagnetic signal to change the client's brain waves while he/she is motionless and with the eyes closed; (ii) Live Z-score neurofeedback, which compares the variables of brain electrical activity to a systematic database continuously in order to provide continuous feedback on the client's performance; (iii) Low-resolution electromagnetic tomography (LORETA), which involves the use of 19 electrodes to monitor multiple variables of the brain electrical activity such as phase, power, and coherence; (iv) Slow cortical potential neurofeedback (SCP-NF), which improves the direction of slow cortical potentials. SCP protocol is used to improve attention in children with ADHD because SCP appears to be attenuated in ADHD during attention tasks; and (v) Frequency/ power neurofeedback, which is used to change the amplitude or speed of specific brainwaves in particular brain locations. It is a common NF protocol used in ADHD [17].

Different Types of Frequency/Power Neurofeedback Training Protocols

In neurofeedback training a child is taught to self-regulate own brain functions through measuring the brainwaves and providing feedback signals during a task. He/she is asked to focus on the visual feedback provided by the neuroimaging modality (i.e., EEG) during training. Through this way, the child can learn how to sustain attention on a target and subsequently improve their attention. For instance, when a child is playing a computer game, electroencephalogram (EEG) sensors are placed on the scalp of the child in order to monitor the brainwaves during the game. If the EEG sensors pick up the brainwaves that show the child is able to control the game using his/her brain (e.g., concentrates at the game), a "reward" signal or sound will be heard. This way will let the child learn how it feels when he/she is concentrating, subsequently it can train him/her to have more control (better attention) to make brainwaves that can reduce ADHD symptoms [18, 19]. A study showed that about 10% of children with ADHD have received NF training and positive effects were found [20]. Neurofeedback training has also been used in different neurological disorders such as depression [21], schizophrenia [22], neuroses [23], post-traumatic stress disorders (PTSD) [24], and Alzheimer's disease [25]. It has been shown to be related to improvement in attention [26–28], memory [26, 28, 29], inhibitory control [30], and motivation [31].

EEG waves can be divided into different bands by frequency, such as delta waves (up to 4 Hz), theta waves (4–8 Hz), alpha waves (8–13 Hz), and beta waves (beyond 13 Hz) [32]. The various types of frequency/power NF training protocols are classified based on these four brainwaves types. (a) Delta waves protocol—Delta waves are associated with deep stage of the non-rapid eye movement (NREM) sleep which is also called slow-wave sleep [32], they are usually found in the frontal and cingulate cortex [33]. Delta waves protocol has been used to alleviate headaches, traumatic brain injury, and learning disorders [34]; (b) Theta waves protocol—Theta waves increased during arousal, memory, emotion, meditation, and sleep [35], which are commonly found in the frontal cortex [36]. Theta waves protocol is used to reduce anxiety, depression, day-dreaming, distractibility, emotional disorders, and ADHD [34]; (c) Alpha waves protocol—Alpha waves increased during sensory stimulation [37, 38], memory [39] and attentional processes [40], they are seen in the posterior regions (occipital and parietal areas) of the brain on both sides [41]. Alpha waves protocol is usually used for the treatment of pain, stress and anxiety, memory, mental performance, and brain injuries [17]; (d) Alpha/Theta waves protocol—NF training may combine alpha and theta waves in the protocol, and this training has been used for alleviating stress, deep levels of depression, addiction, and anxiety [42, 43] or for improving creativity, relaxation, musical performance, and promotes healing from trauma reactions [17]; (e) Beta waves protocol. Beta waves are commonly observed in an awaken condition and are involved in conscious and logical thinking [35], they are commonly found in the frontal-central regions of the brain [44]. Beta waves protocol has been used to improve focus and attention, and reading ability [17] and; (f) Theta/Beta waves protocol. Theta and Beta waves are combined and used in the Theta/Beta waves protocol. It is the most commonly used protocol used in ADHD.

Effects of Theta/Beta Waves Neurofeedback Training in Individuals with ADHD

Both theta and beta waves are found to be related to arousal and attention [45]. Evidence shows that children with ADHD are characterized by increased theta waves and decreased beta waves activities (i.e., high theta-to-beta ratio) [46–49]. Thus, theta and beta waves are targeted in NF training and this theta/beta waves protocol is used to treat ADHD symptoms and related problems. Some studies have examined the effects of NF training focused on suppressing the theta waves and enhancing the beta waves activities (i.e., to lower the high theta-to-beta ratio) in children with ADHD. Results demonstrated that theta/beta waves NF protocol had benefits for attention problems in children with ADHD [50–56].

A systematic review has examined the effects of NF on ADHD symptoms in children and adolescents. Thirteen studies involved theta/beta waves and/or slow cortical potential (SCP) NF protocols were included in this review. Both laboratory tasks and rating scales were used to measure ADHD symptoms. Results showed small effects on ADHD inattention and hyperactivity/impulsivity symptoms based on the reports of least blinded raters (i.e., parents). However, all findings became non-significant when the analyses were done on probably blinded measures (i.e., teacher-rated measures) used in studies with active/sham controls. Besides, effects on laboratory measures of inhibition and attention were not significant [57]. The authors concluded that evidence from studies with probably blinded and laboratory measures fails to support NF as an effective therapy for ADHD. A recent review has examined the effectiveness of NF treatments in adults with ADHD. Nine studies involved theta/beta waves and/or SCP protocols were included for analyses. Small-to-Medium effects were found on inattention and hyperactivity/impulsivity symptoms [58]. The authors concluded that NF therapy plays an important role in reducing ADHD symptoms in adults. In this review, both laboratory tasks and rating scales were used to measure ADHD symptoms but the treatment effects from each type of measure were not analysed separately. It is unclear if the effects would be still significant when either type of measure such as laboratory tasks was considered in the analyses. In addition, because the self-report version of rating scales was used, the training effects might have been influenced by reporters' bias.

The results of these two review papers were inconsistent, the inconsonance is possibly due to the differences in the selection criteria for the studies such as the ages of the participants (there are developmental changes of attention from childhood to adulthood, for example, an adult will have longer attention span than a child; better attention control can facilitate NF training), the years of publication, and the methods of analyses. In order to determine if NF trainings have benefits for attention in children with ADHD, this systematic review and meta-analysis would extend the review done by Cortese and colleagues and included more recently published studies for synthesis and analysis so that the statistical power could be improved. Additionally, the present meta-analysis also examined the long-term effects of theta/beta waves NF training relative to other treatments in children with ADHD by looking specially at the Follow-up period of studies (i.e., Pre-treatment- and- Follow-up comparisons). This way not only could provide information about the plausibility of the sustainable effects of NF training, but also able to control for the non-specific treatment effects of theta/beta NF training (e.g., positive expectation of changes due to training). Although both SCP and theta/beta training protocols have been used to treat inattention symptoms, literature showed that these two NF training protocols have different neuromechanisms for improving attention. SCP training was associated with increased continent negative variation (CNV) amplitudes. CNV refers to a slow, negative-going waveform, which is often observed in the central and frontal areas. It is typically elicited by S1-S2 paradigms in which the child first experiences a warming single (S1), followed by a time period (e.g., 500–1000 ms), and then a response to a latter target stimulus (S2). In the S1-S2 interval, there are early and late CNV components. Early CNV is considered as indicator of arousal processes, and late CNV is associated with attention to the experimental task. A larger CNV was observed when a child was required to behaviorally respond to the S2 [59]. Theta/beta training was associated with increased response speed and targeted P3 amplitude [60]. P3 wave is an event-related potential (ERP) component elicited in the process of decision making. It is usually elicited using the oddball paradigm in which infrequent target items are mixed with frequent non-target items. The child is instructed to respond to the infrequent target stimuli and not to the frequently presented stimuli in the oddball task. When recorded by EEG, it surfaces as a positive deflection in voltage with a latency (delay between stimulus and response) of roughly 250–500 ms. The latency is interpreted as the speed of discriminating one event from another. Shorter latencies indicate better mental performance relative to longer latencies. P3 amplitude seems to reflect stimulus information such that greater attention produces larger P3 waves. P3 wave can be divided into two components: P3a and P3b. The P3a, or novelty P3, has a positive-going amplitude that displays maximum amplitude over frontal/central electrode sites and has a peak latency in the range of 250–280 ms. The P3a has been associated with brain activity related to engagement of attention and the processing of novelty. P3b reflects orienting of attention associated with stimuli that are rare and novel. It is elicited when a child is asked to complete a task that requires attention to deviant stimuli [61]. These two NF protocols have different effects on attentional processes. In order to be more focused, only the effects of theta/beta NF protocols were analysed in this systematic review and meta-analysis.

Objective of this Systematic Review and Meta-analysis

The major objective of this systematic review and meta-analysis was to evaluate the effects of theta/beta waves neurofeedback training on attention in children with ADHD particularly by considering the control conditions and measures used.

Methods

The PRISMA 2020 checklist [62] was used as a reporting guideline for this systematic review and meta-analysis.

Search Strategy

A literature search was conducted in five electronic databases, including PsycINFO, PubMed, ScienceDirect, Scopus, and Web of Science. Keywords under the guidelines of the PICO framework was used for the literature search. The keywords included (a) Participant (P)—attention deficits hyperactivity disorder OR ADHD OR attention problems OR inattention OR attention deficit disorder OR ADD AND child OR pediatric OR adolescent OR teenager OR youth OR kid OR young; (b) Intervention (I)-neurofeedback OR theta/beta neurofeedback OR EEG OR theta wave OR beta wave OR EMG biofeedback; (c) Comparison (C)—physical activity OR exercise OR yoga OR attention training OR cognitive training OR executive function training OR behavioural therapy OR behavioural management OR cognitive behavioural therapy OR stimulant medication OR methylphenidate OR Ritalin OR Adderall OR Vyvanse and; (d) Outcome (O)—attention OR inattention OR ADHD symptoms. After removing duplicate studies, each publication was screened by title and abstract by five reviewers (C. T., G. Q., H. C., H. X., and S. R.). Studies met the inclusion and exclusion criteria and have full-text available were selected for analysis by the same reviewers. The detailed process of literature search and screening were shown in Fig. 1.

Inclusion and Exclusion Criteria

Studies were included for analysis if they met the following criteria: (a) targeted at children or adolescents (both boys and girls) with ADHD aged 6–18 years; (b) at least one condition used theta/beta waves neurofeedback as intervention; (c) included neuropsychological/behavioral measures or rating scales such as parent- or teacher-rating or self-reporting of attention as the primary outcome and; (d) be published in English up to December 31, 2020. Studies were excluded if they were: (a) review, meta-analysis, book, conference paper, or study protocol; (b) targeted at participants aged above 18 years; (c) focused on other neurodevelopmental disorders instead of ADHD; (d) not measured attention as the primary outcome and; (e) not published in English.

Data Extraction and Analysis

The following data were extracted from each study for analysis: (a) study characteristics, (b) participant characteristics, (c) intervention protocols, (d) outcome measures and, (e) main findings Effect sizes (Hedges' g) were computed based on mean, standard deviation (SD), and sample size provided in each included study.

Methodological Quality Assessment

The Physiotherapy Evidence Database Scale (PEDro) [63] was used to evaluate the quality of the included randomized controlled trials (RCTs). Each study was assessed by two reviewers (H. X. and S. R.) independently in order to avoid bias. If inconsistent ratings between reviewers for the same study existed, discrepancies were resolved by discussion between the two reviewers. The PEDro consists of 11 items and a point will be given to an item if the criterion of that item is met. Item 1 does not carry a point, and the total score of the PEDro is the sum of the points of Items 2 to 11, the maximum score is 10. Literature suggests that studies have the total score more than 5 are considered as have adequate methodological quality [64]. In this review, the PEDro total score between 9 and 10 is considered as excellent, score between 6 and 8 is considered as good, score between 4 and 5 is considered as fair, score less than 4 is considered as poor [65].

The Methodological Index for Non-randomized Studies (MINORS) [66] was used to assess the methodological quality of the included non-randomized trials (non-RCT). Two reviewers (H. C. and H. X.) evaluated each study independently in order to avoid bias, disagreements were resolved by discussion and agreement between the reviewers. The MINORS consists of 12 items, the first 8 items are for both non-comparative and comparative trials, while the last 4 items are additional criteria for comparative studies only. An item is scored 0 if no information is reported in the study, a score of 1 is given if related information is reported but not adequate, and a score of 2 is given if information is adequately reported in the study. The maximum total score for non-comparative studies is 16, and that for comparative studies is 24. A comparative study is considered to have high quality if the total MINORS score was ≥ 17 and low quality if the total score was < 17 [67].

Risk of Bias Assessment

The Revised Cochrane Risk of Bias Tool for Randomized Trials (ROB 2) [68] and the Risk of Bias in Non-Randomized Studies—of Interventions (ROBINS-I) [69] were used to assess risk of bias in the selected randomized studies and non-randomized studies respectively. The ROB 2 evaluates the risk of bias in the results of randomized trials in five domains: (a) randomization process; (b) deviations from intended intervention; (c) missing data; (d) outcome measurement and; (e) selection of reported result.

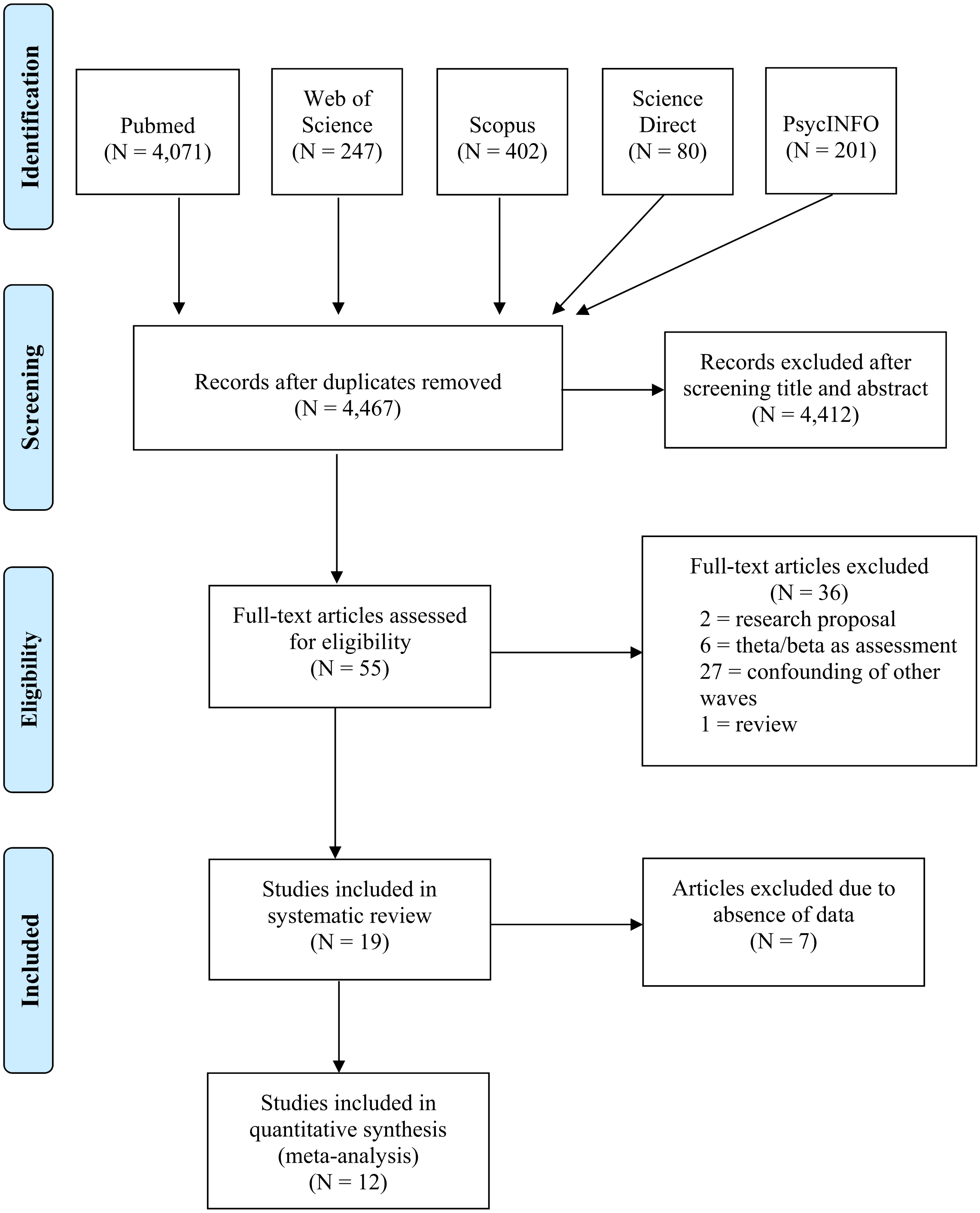

Fig. 1 PRISMA flow diagram for selecting the studies. Note. PRISMA = Preferred Reporting Items in Systematic Reviews and Meta-Analyses

The ROBINS-I assesses the risk of bias in the results of non-randomized trials in seven aspects: (a) confounding; (b) selection of participants; (c) classification of interventions; (d) deviation from intended intervention; (e) missing data; (f) measurement of outcomes and; (g) selection of the reported result. The judgement of risk of bias at both domain and overall levels were made according to the guidelines of both risk of bias assessment tools. Within each domain, a series of signalling questions are designed to collect information about features of each trial that are relevant to risk of bias. A judgement about the risk of bias is made based on the answers of the questions. Judgement can be "Low" or "High" risk of bias, or "Some concerns" for ROB 2, and for ROBINS-I the judgement can be "Low", "Moderate", "Serious", "Critical" risk of bias or "No information" [69, 70]. The risk of bias was evaluated by two reviewers (C. T. and G. Q.), disagreements were resolved by discussion and agreement between the two reviewers.

Meta-analysis and Publication Bias

A meta-analysis of the effects of the theta/beta waves neurofeedback training on attention in children with ADHD was conducted using the Comprehensive Meta-Analysis 3.0 program (CMA, Version 3.0) [71]. The effect sizes (Hedge's g) for three types of comparisons on the measure of attention of each study were calculated: (a) Within-group effect sizes which were based on the Pre- and Post-treatment comparison of the Intervention Group; (b) Between-group effect sizes which were based on the between-group differences from Pre-treatment to Post-treatment and; (c) Long-term Within-group effect sizes which were based on the Pre-treatment and Follow-up comparison of the Intervention Group. The strength of the effect size is considered as small if Hedges' g is 0.2; medium if Hedges' g is 0.5; and large if Hedges' g is 0.8 [72].

Publication bias was evaluated by computing the Egger's regression test using the standard errors of the effect sizes of the reviewed studies. Funnel Plot was performed if the number of studies reviewed was ≥ 10 [73]. Funnel Plot Asymmetry was tested using the Trim-and-Fill method. The significance level for publication bias was set to 0.1 [74].

Results

Trial Flow

A total of 5001 studies were yielded after the search from five databases (PsycINFO, PubMed, ScienceDirect, Scopus, and Web of Science) using the selected keywords. After removing duplicates, 4467 studies were left for further screening. Based on the title and abstract, 4412 studies were screened out, and 55 studies were further screened for appropriateness based on the selection criteria. Full-text were available for all 55 studies, among them, 36 studies did not fulfil the selection criteria and were excluded. Finally, 19 studies were selected for evaluation in this systematic review, and only 12 studies had the required data for effect sizes calculation and they were included for meta-analysis. The literature selection process was shown in Fig. 1.

Study Characteristics

The 19 included studies were published between 2007 and 2020 (Table 1). For study design, 13 studies were randomized controlled trials (RCTs) [50–53, 55, 56, 75–81] and 6 were non-randomized controlled trials (non-RCTs) [30, 82–86] in which two trials had quasi-experimental design [85, 86] and four were clinical controlled trials (CCT) [30, 82–84] (Table 1).

Theta/beta waves NF protocol was the treatment for the Intervention group in all included studies. Regarding the treatment for the comparison groups, one study had a wait-list control group which received the same treatment as the Intervention group after the waiting period [30]; three studies received conventional treatment such as treatment as usual (TAU) [80], attention skills training [77], and behavioural training [56]; two studies [52, 79] involved physical activities such as yoga; eight studies [51, 52, 56, 76, 78, 81, 83, 84] used stimulant medication (methylphenidate); seven studies used other types of NF protocols such as slow cortical potential NF [53, 77], sensorimotor rhythm-based neurofeedback training (SMR-based NF) [86], theta/alpha waves neurofeedback training [85], EMG-biofeedback [50, 55]; and sham neurofeedback [75]; three studies [51, 76, 84] involved combined theta/beta waves NF and stimulant medication; and two studies [79, 84] received no treatment (Table 1).

Participant Characteristics

A total of 1059 children aged between 6 and 18 years with ADHD were involved in this systematic review (Table 1). All except three studies [76, 79, 85] had reported the number of boys and girls separately, the boys-to-girls ratio was 3.29 [boys (n) = 665; girls (n) = 202]. Regarding the use of stimulant medication during the study period, nine studies [51, 52, 56, 76–78, 81, 84, 85] reported that all children of the Intervention group were medication naïve; four studies [50, 80, 83, 86] reported children were asked to keep the medication levels constant during study period; two studies [55, 75] had asked children to suspend the use of stimulant medication at least 2 days before the major assessments; one study [30] reported the number of children continued and the number of children discontinued to use stimulant medication during the study period separately; two studies [53, 82] only reported the number of children who were on stimulant medication before the start of study but had not provided any information about children's medication condition during the study period; and one study [79] had not reported any information regarding children's use of stimulant medication. For comorbidities, all except two studies [79, 84] had reported the comorbid conditions of children. Four studies [56, 83, 85, 86] included children with ADHD who had no comorbidities. One study [78] included children with ADHD and comorbid oppositional defiant disorder. Six studies [50, 52, 53, 55, 77, 80] included children with conduct disorders, emotional disorders, anxiety disorders, depressive disorders or learning difficulties, while one study

Table 1 Characteristics and major findings of the reviewed studies

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG				Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity				
Arnold et al. [75]	RCT	8.51 (1.17)	65/19	8.67 (1.1)	46/12	23 children took stimulant medication, continued stimulants during treatment period but discontinued for 5 days before major assessments. / Children with comorbid disorders requiring psychoactive medication other than psychostimulant were excluded	Theta/beta-based NF: Theta wave 4–8 Hz, Beta wave 13–21 Hz	38 treatments in 14 weeks;	18 children took stimulant medication and continued stimulants during treatment period but had to discontinue for 5 days before major assessment / Same as IG	Sham NF	Same as IG	Parent- and Teacher-rating on inattentive symptoms on the Conners 3rd edition	Both groups showed significant improvements on attention at Post-treatment.	IG: Improvements were non-significant at Follow-up	IG was not significantly superior to CG at both Post-treatment and Follow-up

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG						
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity		Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
Bakhshayesh et al. [50]	RCT	9.6 (2.2)	13/5	9.1 (1.6)	13/4	4 children took stimulant medication Children were asked to keep medication level constant throughout the training period / Children had Conduct disorder, Emotional disorder, & Motor skills disorder / dyslexia were also included	Theta/beta-based NF: Theta wave 4–8 Hz, Beta wave 16–20 Hz	30 min/session × 30 sessions across 10–15 weeks	3 children took stimulant medication Children were asked to keep medication level constant throughout the training period / Same as IG	EMG-BF	Same as IG	Parent- and Teacher-rating on inattentive symptoms on the FBB-HKS/ADHS; bp/d2 Test; CPT	IG showed significant improvements on attention at Post-treatment	N/A	IG > CG

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG						
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity		Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
Bluschke et al. [30]	CCT with Wait-list control	11.2 (2.0)	18/1	11.3 (2.1)	17/0	9 children took stimulant medication. 5 of them were tested under medicated state / Children had psychiatric (e.g. autism, tics, depressive episode) or somatic comorbidities were excluded	Theta/beta-based NF: Theta wave 4–8 Hz, Beta wave 13–20 Hz	1 h/session × 16 sessions across 8 weeks	9 children took stimulant medication 4 of them were tested under medicated state / Same as IG	Same as IG	Same as IG	Parent-rating on inattentive symptoms on the CPRS	IG showed significant improvements at Post-treatment	N/A	IG > CG

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG				Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity				
Bluschke et al. [82]	CCT	ADD 10.9 (1.9) ADHD-C 11.5 (2.1)	ADD 13/4 ADHD-C 16/3	Healthy control 11.3 (2.2)	14/5	ADD 8 children took stimulant medication ADHD-C 9 children took stimulant medication / Children were excluded if there were severe or acute psychiatric (e.g. autism, tics, depressive episode) or somatic comorbidities	Theta/beta-based NF: Theta wave 4–7 Hz, Beta wave 16–25 Hz;	1 h/session × 16 sessions across 8 weeks	No children took stimulant medication / Same as IG	No treatment	N/A	Parent-rating on inattentive symptoms on the ADH-DRS	IG showed significant improvements at Post-treatment	N/A	IG > CG

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG				Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity				
Duarte-Hernández et al. [83]	CCT	PI group 11.57 PH group 11.91	PI group 11/5 PH group 14/6	12.25	8/6	All children took stimulant medication and were asked to keep the medication level constant during training / Only children did not exhibit other comorbidities were included in this study	Theta/beta-based NF: No information of brain wave frequencies provided	25 min/session × 25 sessions across 12.5 weeks	All children took stimulant medication / Same as IG	On MPH	To keep medication level constant during the study period	IVA/CPT	PI group showed significant improvements at Post-treatment	N/A	PI > PH, CG
Duric et al. [76]	RCT	11.4 (3.1)	22/8	CG 1 10.9 (2.4) CG 2 11.2 (2.8)	CG 1 27/4 CG 2 23/7	All children were medication naïve / Children with comorbid disorders were also included but comorbidities were not reported	Theta/beta-based NF: Theta wave 4–7 Hz, Beta wave 16–20 Hz	40 min/session × 30 sessions across 10 weeks	All children were on stimulant medication twice per day during study period / Same as IG	CG 1 MPH CG 2 NF + MPH	CG 1 On MPH twice/day CG 2 NF- same as IG MPH—twice per day	Parent-reporting on inattentive symptoms on the Clinician's Manual of Disruptive Behavior Disorders Rating Scale	Improvements were observed in all groups at Post-treatment	N/A	No significant dfiiferences between groups

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG				Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity				
Duric et al. [51]	RCT	11.4 (3.1)	28 children in total	CG 1 10.9 (2.4) CG 2 11.2 (2.8)	CG 1 27 children in total CG 2 25 children in total	All children were medication naïve / Children with comorbid disorders were also included but comorbidities were not reported	Theta/beta-based NF: Theta wave 4–7 Hz, Beta wave 15–20 Hz	45 min/session × 30 sessions across 10 weeks	All children took stimulant medication, twice per day during study period / Same as IG	CG 1 MPH CG 2 NF + MPH	CG 1 On MPH twice/day CG 2 NF- same as IG MPH—twice per day	Self-reporting on inattentive symptoms on the Self-rating Scale (SRQ)	Improvements were observed in all groups at Post-treatment	N/A	No significant differences between groups
Geladé et al. [52]	RCT	9.81 (1.86)	24/9	CG 1 8.97 (1.22) CG 2 9.55 (1.76)	CG 1 22/6 CG 2 24/7	All children were medication naïve / Comorbid disorders included learning disorders, autism spectrum disorders, anxiety disorders, and mood disorder	Theta/beta-based NF: Theta wave 4–8 Hz, Beta wave 13–20 Hz	45 min/session × 30 sessions across 10–12 weeks	CG1 On MPH CG2 All children were medication free / Same as IG	CG 1 MPH CG 2 PA	CG 1 Twice/day CG 2 20 min of exercises/session × 30 sessions	Parent- and Teacher-rating on inattentive symptoms on the SWAN; AOT	Improvements were observed in all groups at Post-treatment	Improvements were observed in all groups at Follow-up	CG1 > IG, CG2 on parent-reported attention at Post-treatment; IG > CG2 on teacher-reported attention at Follow-up

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG				Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity				
Gevensleben et al. [77]	RCT	9.10 (1.3)	51/8	9.4 (1.2)	26/9	All children were medication naïve / Children with comorbid disorders other than conduct disorder, emotional disorders, tic disorder and dyslexia were excluded	Theta/beta-based + SCP NF: Theta and beta wave 1–30 Hz SCP wave 0.01–30 Hz	50 min/session × 18 sessions across 3 weeks	All children were medication free / Same as IG	Attention skills training (AST)	50 min/session × 18 sessions across 3 weeks	Parent- and Teacher-rating on inattentive symptoms on the FBB-HKS/ADHS	Both groups showed improvements on attention as rated by parents and teachers	N/A	IG > CG on both parent- and teacher rated attention
González-Castro et al. [84]	CCT	9.63 (1.20)	22/11	CG 1 9.63 (1.14) CG 2 9.67 (1.10) CG 3 9.52 (1.02)	CG 1 22/11 CG 2 19/15 CG 3 20/11	All children were medication naïve / Comorbid disorders not reported	Theta/beta-based NF: No information of brain wave frequencies provided	15 min/session, 3 sessions/ week × 3 months	CG1 All children were medication free CG2 On MPH CG3 On MPH / Same as IG	CG 1 No treatment CG 2 On MPH CG 3 NF + MPH	CG 1 N/A CG 2 Dosage based on age and weight CG 3 NF – same as IG; MPH – same as CG2	Parent-rating on inattentive symptoms on the EDAH; TOVA	All groups showed improvements at Post-treatment	N/A	CG3 > IG, CG1, CG2; IG > CG1

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG				Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity				
Leins et al. [53]	RCT	9.16 (1.46)	16/3	9.16 (1.53)	16/3	One child was on stimulant medication / One child in the IG had emotional disorder; while four children had learning disorders and one child had coordination disorder in CG	Theta/beta-based NF: No information of brain wave frequencies provided	10 sessions across 2 weeks per treatment phase × 3 treatment phases	One child was on stimulant medication / Same as IG	SCP-NF No information of brain wave frequencies provided	10 sessions across 2 weeks per treatment phase × 3 treatment phases	Parent-rating on inattentive symptoms based on DSM IV criteria	Both groups showed improvements	Both groups showed improvements	No significant group differences at Post-treatment and Follow-up

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG				Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity				
Maurizio et al. [55]	RCT	10.6 (1.3)	11/2	10.0 (1.2)	11/1	One child was on stimulant medication Child was assed to suspend medication at least 48 h before assessments / Only children had no severe comorbid conduct disorders, depression or anxiety disorders were included	Theta/beta-based NF: Theta wave 4–7.5 Hz, Beta wave 14–20 Hz	12–32 min/session × 36 sessions across 12 weeks	One child was on stimulant medication Child was asked to suspend medication at least 48 h before assessment / Same as IG	EMG-biofeedback 55-95 Hz	Muscle activity (55–95 Hz) of both arms	Parent-rating on inattentive symptoms on the FBB-HKS/ADHS and the CPRS; Teacher-rating on inattentive symptoms on the CTRS	Both groups showed improvements	N/A	No significant group differences at Post-treatment
Meisel et al. [78]	RCT	9.53 (1.80)	6/6	8.90 (1.53)	6/5	All children were medication naive / Children with comorbid disorders (other than oppositional defiant disorder) were excluded	Theta/beta-based NF: Theta wave 4–7 Hz, Beta wave 15–20 Hz	24 min/session, 2 sessions/week, in total 40 sessions	On MPH / Same as IG	On MPH	1 mg/kg/day of MPH for 20 weeks and continued in follow-up period	Parents- and Teacher-rating on inattentive symptoms on the ADHDRS-IV	Both groups showed improvements	Both groups showed improvements	No significant group differences at Post-treatment and Follow-up

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG						
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity		Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
Mohaghegh et al. [85]	Quasi-experiment	8.51 (1.44)	N = 26	8.51 (1.44)	N = 28	All children were medication naïve / Children had psychiatric disorders other than ADHD were excluded	Theta/beta-based NF: Theta wave 4–7 Hz, Beta wave 12–15 Hz	45 min/session, 3 sessions/week, in total 40 sessions	All children were medication naïve / Same as IG	Theta/alpha-based NF Theta wave4-7 Hz, Alpha wave 10–12 Hz	45 min/session, 3 sessions/week, in total 40 sessions	Parent-rating on inattentive symptoms on the CPRS-R; CPT-II	Both groups showed improvements	Both groups showed improvements	IG > CG at Post-treatment and Follow-up
Mohammadi et al. [86]	Quasi-experiment	9–15 years	13/3	9–15 years	13/3	All children were on stimulant medication during study period / Children had psychiatric disorders other than ADHD were excluded	Theta/beta-based NF: Theta wave 4–7 Hz, Beta wave 15–18 Hz	45 min/session, 2 sessions/week, in total 30 sessions	All children were on stimulant medication during study period / Same as IG	SMR/theta-based NF SMR wave 12–15 Hz, Theta wave 4–7 Hz	45 min/session, 2 sessions/week, in total 30 sessions	Parent-rating on inattentive symptoms on the ADH-DRS; d2 test	Both groups showed improvements	Both groups showed improvements	IG > CG at Post-treatment and Follow-up

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG				Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity				
Moreno-García et al. [56]	RCT	9.21 (1.9)	15/4	CG 1 9.21 (2.2) CG 2 8.11 (1.3)	CG 1 15/4 CG 2 14/5	All children were medication naive / Children had comorbid disorders were excluded	Theta/beta-based NF: Theta wave 4–7 Hz, Beta wave 15–20 Hz	24 min/session, 4 sessions/week for a total of 30 sessions	CG 1 On MPH CG 2 All children were medication naive / Same as IG	CG 1 On MPH CG 2 Behavioural therapy	CG 1 1 mg/kg/day during study period CG 2 Child- 15 sessions of CBT; Parent—10 weekly training sessions; Teacher- 5 group training sessions	IVA/CPT	All groups showed improvements	All groups showed improvements	CG1 > IG, CG2 at Post-treatment and Follow-up
Rezaei et al. [79]	RCT	7–11 years	N = 7	7–11 years	CG 1 N = 7 CG 2 N = 7	No information provided / Comorbid disorders not reported	Theta/beta-based NF: No information of brain wave frequencies provided	45 min/session × 24 sessions across 8 weeks	No information provided / Same as IG	CG 1 Yoga CG 2 No treatment	CG 1 45 min/session × 24 sessions across 8 weeks CG 2 N/A	CPT	All groups showed improvements	N/A	IG, CG1 > CG2 at Post-treatment

Table 1 (continued)

Study	Study design	Participant characteristics				Intervention protocol						Measures of attention	Major findings		
		IG		CG		IG			CG						
		Age X(SD)	M/F (n)	Age X(SD)	M/F (n)	Medication/ Comorbid Disorders	Treatment received	Treatment intensity	Medication/ Comorbid Disorders	Treatment received	Treatment intensity		Pre- and Post-treatment comparisons	Pre-treatment and Follow-up comparisons	Between-group comparisons
Shereena et al. [80]	RCT	8.7 (1.83)	13/2	9.7 (2.38)	15/0	One child was on medication during study period / Children with comorbid disorders other than conduct disorder, specific learning disability, and emotional disorder were excluded	Theta/beta-based NF: Theta wave 4–7 Hz, Beta wave 15–18 Hz	3–4 sessions/week for 3.5–5 months for a total of 40 sessions	Three children were on medication during study period / Same as IG	TAU Routine clinical management	Same as IG	Shereena et al. [80]	IG showed improvements	IG showed improvements	IG > CG at Post-treatment and Follow-up
Sudnawa et al. [81]	RCT	8.4 (1.6)	18/2	9.0 (1.5)	18/2	All children were medication naive / Children had conduct disorder, anxiety disorder, or depressive disorder were excluded	Theta/beta-based NF: Theta wave 4–8 Hz, Beta wave 13–20 Hz	30 min/session × 30 sessions across 12 weeks	All children were on MPH / Same as IG	MPH	5 mg twice daily ((at breakfast and lunch time)	Parent- and Teacher-rating on inattentive symptoms on the Vanderbilt ADHDRS	Both groups showed improvements on parent- and teacher-rated attention at Post-treatment	N/A	No significant group differences on parent-rated attention CG > IG on teacher-rated attention

RCT, randomized controlled trial; CCT, clinical controlled trial; IG, intervention group; CG, comparison group; MPH, methylphenidate; NF, neurofeedback; ADHD-C, ADHD combined type; ADD, attention deficit disorder; PI, predominantly inattentive subtype; PH, predominantly hyperactive subtype; PA, physical activity; SCP, slow cortical potential; SMR, sensorimotor rhythm; EMG-BF, electromyography-biofeedback; AST, attention skills training; TAU, Treatment as usual; CPT, continuous performance test; SWAN, strengths and weaknesses of ADHD symptoms and Normal behaviour scale; AOT, auditory oddball task; FBB-HKS/ADHS, the German ADHD Rating Scale; CCT, color cancellation test; CTT, color trails test; ADHDRS, ADHD Rating Scale; CPRS, Conners' Parent Rating Scale; CPRS-R, The Revised Conners' Parent Rating Scale; CTRS, Conners' Teacher Rating Scale; IVA/CPT, Integrated Visual Auditory Continuous Performance Test; DSM, Diagnostic and Statistical Manual of Mental Disorders; EDAH, Evaluation of Deficit of Attention and Hyperactivity Scale; TOVA, test of variables of attention; N/A, not applicable

[81] excluded children with these comorbid disorders. One study [75] included children with comorbid disorders requiring psychostimulant but not psychoactive medication. Two studies [51, 76] included children with comorbidities but comorbid disorders were not reported. Two studies [30, 82] excluded children with psychiatric disorders such as autism spectrum disorder, depressive episode or somatic comorbidities (Table 1).

Intervention Protocols

Fifteen reviewed studies using the frequencies 4–8 Hz for theta waves and 12–25 Hz for beta wave in the Intervention groups, while four studies [53, 79, 83, 84] had not reported the frequencies used for the treatments. Regarding treatment intensity, the total number of training sessions varied from 15 to 40 [mean (SD) = 27.81 (7.36)], and each session lasted from 15 to 180 min [mean (SD) = 42.60 (25.26)]. The treatment duration ranged between 3 and 20 weeks [mean (SD) = 9.88 (3.25)] (Table 1).

Targets of Intervention

Sohlberg and Mateer (1989) posited that there are four types of attention: sustained attention, selective attention, alternating attention, and divided attention [87]. Among the 19 reviewed studies, eight studies [50, 52, 56, 79, 80, 83–85] measured sustained attention; three studies [50, 80, 86] targeted at selective attention, one study focused on divided attention [80]; and no studies targeted at alternating attention (Table 1). Besides, seven studies [52, 56, 79, 83–86] targeted at one type of attention; and two studies [50, 80] focused on two or more types of attention (Table 1).

Outcome Measures

In total 15 different tools classified into two major types of measures, neuropsychological/behavioural testing and parent- and teacher-rating/self-reporting, were used to assess attention in the 19 included studies. Seven neuropsychological/behavioral tests were used in 9 studies: (i) the Continuous Performance Test (CPT) for sustained attention were used in three studies [50, 79, 85]; (ii) the Integrated Visual Auditory Continuous Performance Test (IVA/CPT) for sustained attention were used in two studies [56, 83]; (iii) the Auditory Oddball Task (AOT) for sustained attention was used in one study [52]; (iv) the Test of Variables of Attention (TOVA) for sustained attention was used in one study [84]; (v) the Colour Cancellation Test (CCT) for selective attention was used in one study [80]; (vi) the Colour Trails Test (CTT) for divided and sustained attention was used in one study [80] and; (vii) the D2 Test for selective attention was used in two studies [49, 50] (Table 1).

Eight different rating scales were used to measure attention in 16 studies. The parent-rating version of the 8 rating scales included: (i) the Conners Parent Rating Scale (CPRS) which was used in three studies [30, 55, 85]; (ii) the Strengths and Weaknesses of ADHD Symptoms and Normal Behaviour Scale (SWAN) which was used in one study [52]; (iii) the ADHD Rating Scale (ADHDRS) which was used in four studies [78, 80, 82, 86]; (iv) the Vanderbilt ADHD Rating Scales was used in one study [81]; (v) the German ADHD Rating Scale (FBB-HKS/ADHDRS) was used in three studies [50, 55, 75]; (vi) the Clinician's Manual of Disruptive Behavior Disorders Rating Scale was used in one study [76]; (vii) the Diagnostic and Statistical Manual of Mental Disorders (DSM) Criteria were used in two studies [53, 75] and; (viii) the Evaluation of Deficit of Attention and Hyperactivity Scale (EDAH) was used in one study [84]. The teacher-rating version of the 5 rating scales included: (i) the Conners Teacher Rating Scale (CTRS) which was used in one study [55]; (ii) the Strengths and Weaknesses of ADHD Symptoms and Normal Behaviour Scale (SWAN) which was used in one study [52]; (iii) the ADHD Rating Scale (ADHDRS) which was used in two studies [78, 80]; (iv) the German ADHD Rating Scale (FBB-HKS/ADHDRS) was used in two studies [50, 77] and; (v) the Diagnostic and Statistical Manual of Mental Disorders (DSM) Criteria were used in one study [75]. Self-reporting using the Self-reporting Questionnaire (SRQ), an author- developed questionnaire, was used in one study [51] (Table 1).

Methodological Quality Assessment

The PEDro total scores of the 13 reviewed RCTs ranged from 4 to 10 points (Table 2), indicating that the methodological quality of the included RCTs was fair-to-excellent. Among all reviewed RCTs, three studies had a PEDro total scores of 4–5 (Fair quality) [76, 77, 80], nine studies had a Pedro score between 6 and 8 (Good quality) [50–53, 55, 56, 78, 79, 81], and one study had a Pedro score of 10 (Excellent quality) [75] (Table 2).

The MINORS total scores of the six non-RCTs evaluated in this review ranged from 11 to 20. Three non-RCTs [30, 85, 86] had the total score between 11 and 14, suggesting a low methodological quality, and the other three studies [81–84] had a MINORS score between 17 and 20, suggesting a high quality (Table 2).

Risk of Bias Assessment

The Risk of Bias assessment showed that among the 13 reviewed RCTs, four trials were evaluated to have an overall low risk [50, 56, 75, 80], seven trials [53, 55, 76–79, 81] had some concerns, and two trials [51, 52] had high risk of bias (Fig. 2). For non-RCTs, four studies [82–85]

Table 2 Methodological Quality Assessment of Randomized Controlled Trials using the PEDro Scale (top) and Non-randomized Controlled Trials using the MINORS (bottom)

Studies	1	2	3	4	5	6	7	8	9	10	11	Total
Arnold et al. [75]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	10
Bakhshayesh et al. [50]	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	7
Duric et al. [76]	Y	Y	N	Y	N	N	N	N	Y	Y	Y	5
Duric et al. [51]	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	8
Geladé et al. [52]	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	8
Gevensleben et al. [77]	Y	Y	N	Y	N	N	N	N	Y	Y	Y	5
Leins et al. [53]	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	7
Maurizio et al. [55]	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	7
Meisel et al. [78]	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	6
Moreno-García et al. [56]	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	7
Rezaei et al. [79]	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	6
Shereena et al. [80]	Y	Y	N	Y	N	N	N	N	N	Y	Y	4
Sudnawa et al. [81]	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	6

Studies	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Total
Bluschke et al. [30]	1	2	1	0	0	1	0	1	0	2	2	1	11
Bluschke et al. [82]	2	2	2	2	0	1	2	2	0	2	1	2	18
Duarte-Hernández et al. [83]	2	2	2	2	0	1	2	1	2	2	1	2	17
González-Castro et al. [84]	2	2	2	2	0	1	2	1	2	2	2	2	20
Mohagheghi et al. [85]	2	2	2	0	0	2	0	1	0	2	2	1	14
Mohammadi et al. [86]	2	2	1	2	0	1	2	1	0	0	0	1	12

PEDro, Physiotherapy Evidence Database; Y, meeting the criteria; N, not meeting the criteria

1: eligibility criteria and source of subjects; 2: randomly allocate; 3: allocation was concealed; 4: similarly, at baseline; 5: all participants blinded; 6: all therapists blinded; 7: assessors blinded; 8: from more than 85% of the participants obtained at least one key outcome; 9: at least one key outcome on 'intention to treat'; 10: between group statistical comparisons; 11: point measures and measures of variability at least one key outcome

Item 1 does not contribute to the total PEDro score

MINORS, Methodological Index for non-Randomized Studies

I: A clearly stated aim; II: Inclusion of consecutive patients; III: Prospective collection of data; IV: Endpoints appropriate to the aim of the study; V: Unbiased assessment of the study endpoint; VI: Follow-up period appropriate to the aim of the study; VII: Loss to follow up less than 5%; VIII: Prospective calculation of the study size; IX: An adequate control group; X: Contemporary groups; XI: Baseline equivalence of groups; XII: Adequate statistical analyses

Ratings: 0 = not reported; 1 = reported but inadequate; 2 = adequately reported

had an overall moderate risk of bias and two trials [30, 86] had serious risk of bias (Fig. 2).

Effects of Theta/Beta Waves Neurofeedback Training

Among the 19 reviewed studies, 12 studies [30, 50, 52, 55, 75, 78, 79, 81, 82, 84–86] have reported the mean and standard deviation of attention measures at both pre-treatment and post-treatment, and seven studies [51, 53, 56, 76, 77, 80, 83] have reported the changes in scores or the baseline scores only. The authors of the latter seven studies have been contacted for the complete data set, however, no reply has been received from them. Therefore, only 12 studies [50, 52, 55, 75, 78–82, 84–86] were included in the meta-analysis.

Pre- and Post-treatment Effects

To evaluate the short-term effect of theta/beta waves NF training, the effect sizes (Hedges' g) were computed based on the comparisons of the mean (SD) and sample size of the Intervention group at Pre- and Post-treatment of each study. Among the 12 studies included in this meta-analysis, all studies reported improvements in attention in children with ADHD after theta/beta waves NF training. The random effects meta-analysis of within-group effect sizes (Hedges' g) for Pre- and Post-treatment comparisons ranged between 0.23 and 1.45, the pooled effect size was 0.65 (95% CI [0.45, 0.84]) (Fig. 3). The funnel plot revealed that the distribution

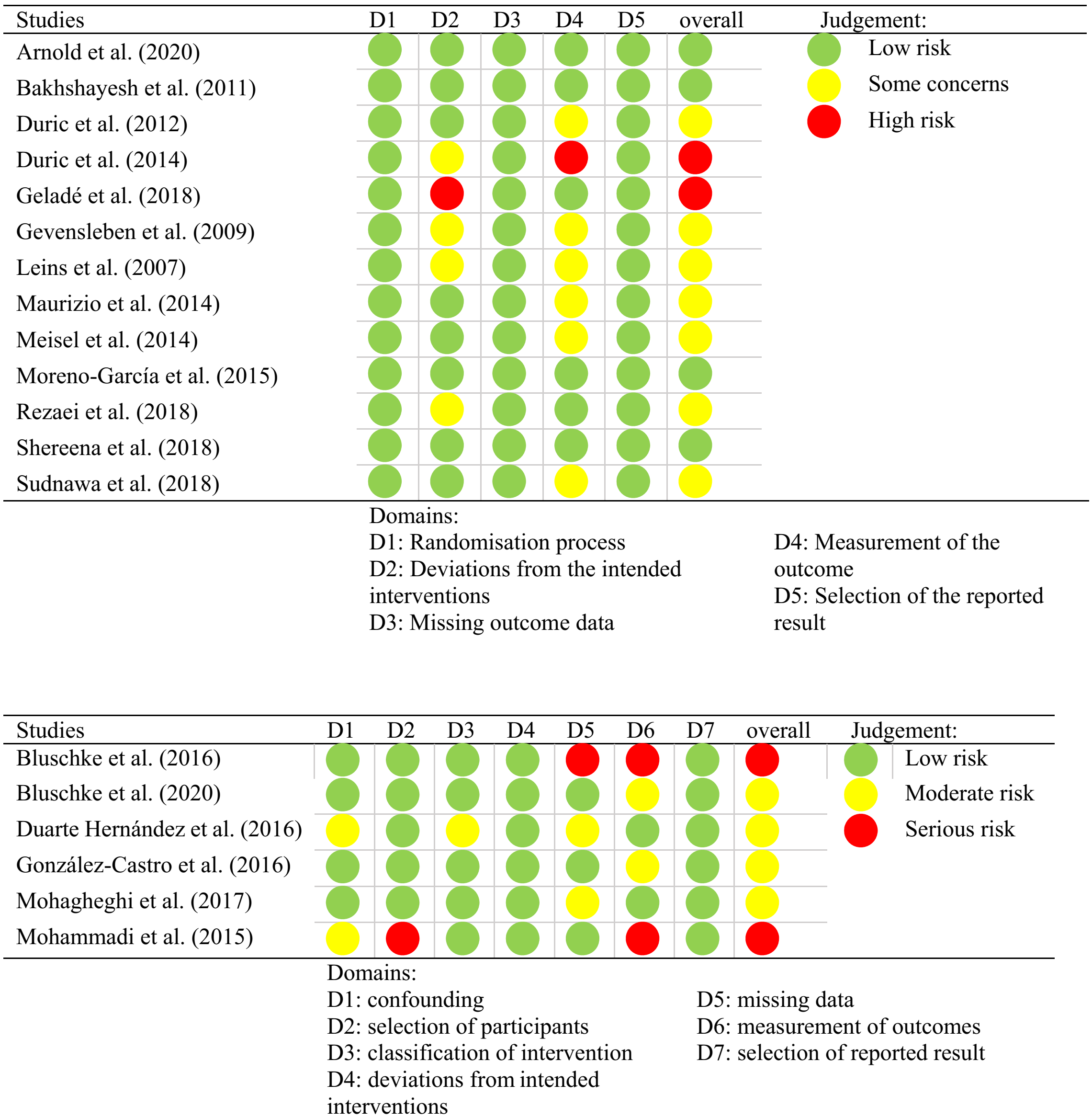

Fig. 2 Risk of bias summary for all randomized controlled trials using the revised cochrane risk of bias tool for randomized trials (ROB 2) (top) and for all non-randomized controlled trials using the risk of bias in non-randomized studies- of interventions (ROBINS-I) (bottom)

of effect sizes was quite symmetrical on both sides of the pooled effect size (Fig. 4). Sensitivity analysis showed that the removal of discrete point [79] did not have a significant impact on the pooled effect size. The Trim-and-Fill method showed that no studies would need to fall to the left of the mean but one study would need to fall to the right of the mean to make the plot symmetrical. The random effects model for the adjusted pooled effect size revealed a Hedges' g = 0.63 (95% CI [0.44, 0.83]). In addition, the Egger's regression intercept was not significant (intercept = 0.29, p = 0.79).

Between-Group Effects

For between-group comparisons, the random effects meta-analysis of between-group effect sizes (Hedges' g) for post-treatment comparisons ranged from—0.70 to 2.78, the pooled effect size was 0.20 (95% CI [− 0.11, 0.51]) (Fig. 3). The Trim-and-Fill method showed that no studies would need to fall to the right of the mean but one study would need to fall to the left of the mean to make the plot symmetrical (Fig. 4). The random effects model for the adjusted pooled effect size revealed a Hedges' g = 0.26 (95% CI [− 0.05, 0.58]). Furthermore, the Egger's regression intercept was not significant (intercept = 1.55, p = 0.37).

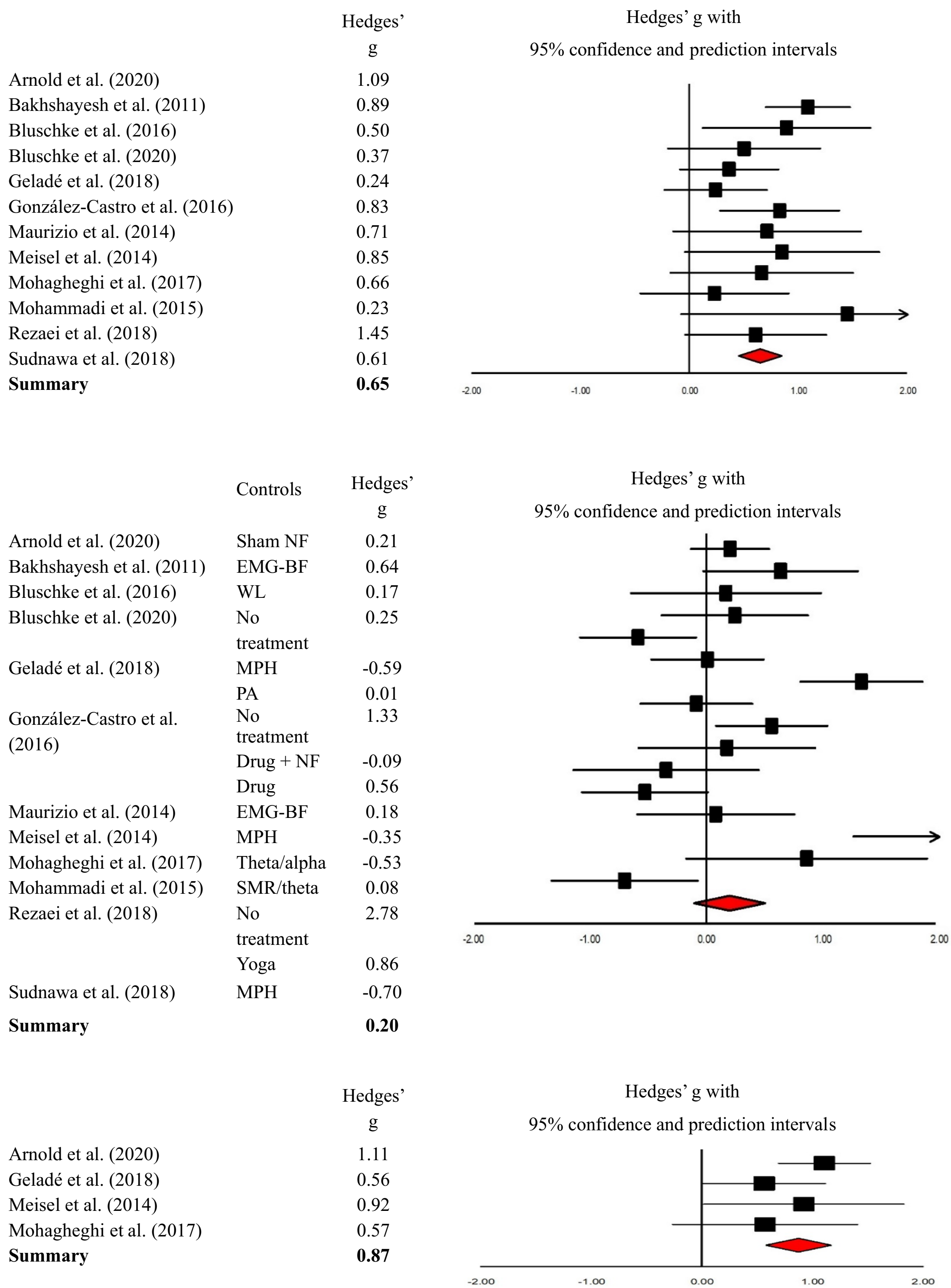

Fig. 3 Random effects model-forest plot for within-group comparisons at post-treatment (top), between-group comparisons (middle), and within-group comparisons at follow-up (bottom)

To further evaluate the effects of theta/beta waves NF training on attention, the effect sizes for the comparisons between theta/beta waves NF training and different control conditions were computed. When compared to a waitlist control group, the effect size (Hedges' g) at post-treatment based on one study [30] was 0.17 (95% CI [− 0.65, 0.99]).

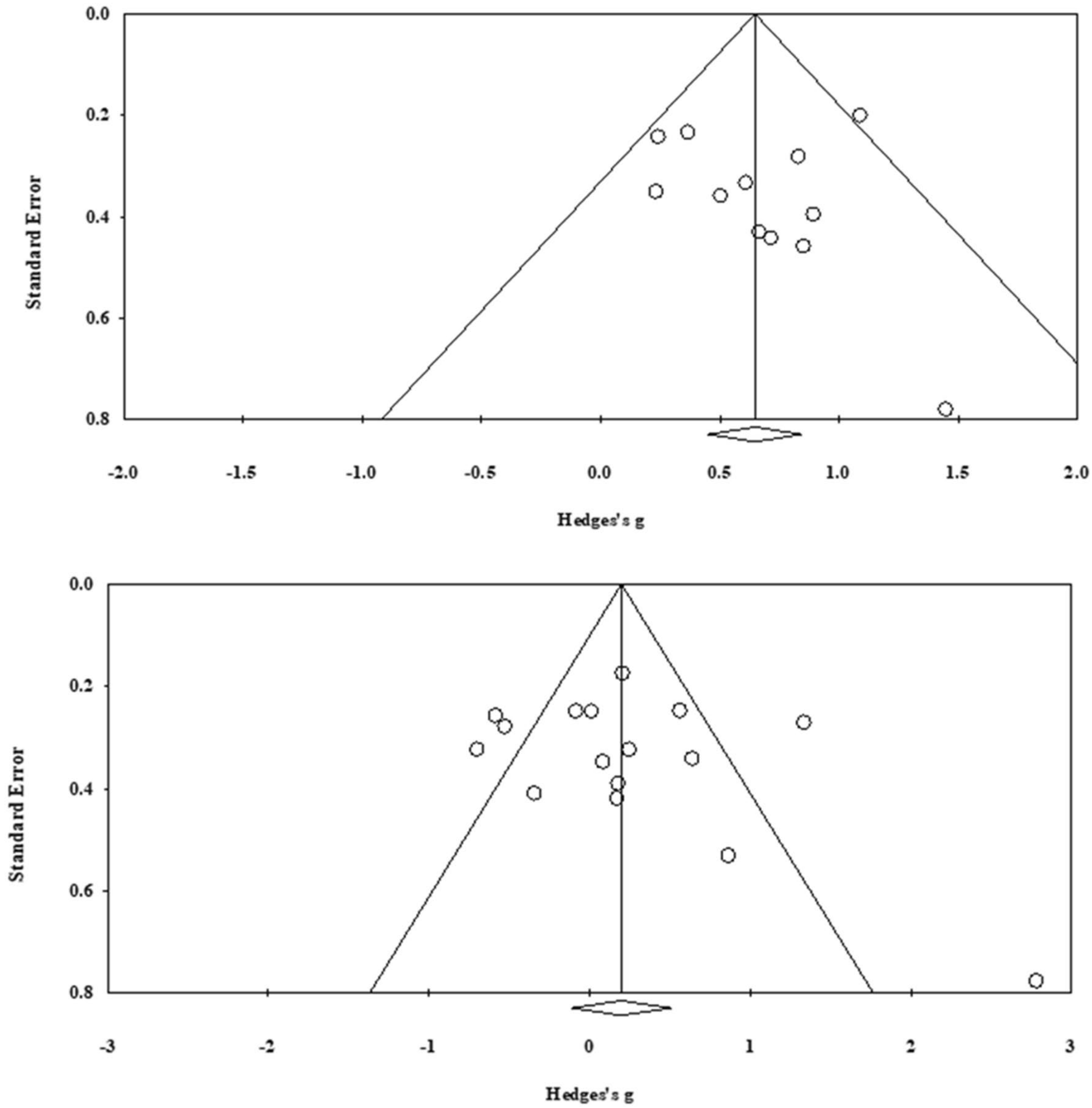

Fig. 4 Within-group funnel plot of standard error by Hedges' g (top) and between-group funnel plot of standard error by Hedges' g (bottom)

The effect sizes for the comparison with physical activities such as yoga based on two studies were 0.01[52] and 0.86 [79], the pooled effect size was 0.31 (95% CI [− 0.49, 1.10]). For stimulant medication (methylphenidate), the effect sizes based on four studies [52, 78, 81, 84] ranged from—0.70 to 0.56, the pooled effect size was—0.25 (95% CI [− 0.89, 0.39]). In these four studies, the effects were in favour of stimulant medication in three studies [52, 78, 81]. When compared to other types of NF protocols, the effect sizes for SMR/theta waves NF based on one study [86] was 0.08 (95% CI [− 0.60, 0.76]); alpha/theta waves NF based on one study [85] was—0.53 (95% CI [− 1.07, 0.02]); sham neurofeedback based on one study [75] was 0.21 (95% CI [− 0.14, 0.55]), and the pooled effect size for other types of NF protocols was − 0.06 (95% CI [− 0.52, 0.41]). The effect size for comparison to combined medication and NF based on one study [84] was—0.09 (95% CI [− 0.57, 0.40]). For EMG-biofeedback, the effect sizes (Hedges' g) based on two studies [50, 55] were 0.18 and 0.64, the pooled effect size was 0.44 (95% CI [- 0.07, 0.94]). The effect sizes for comparisons to no treatment based on three studies [79, 82, 84] ranged from 0.25 to 2.78, the pooled effect size was 1.23 (Hedge's g = 1.23, 95% CI [0.14, 2.36]) (Table 3).

Long-Term Effects

Four studies [52, 75, 78, 85] reported retention of improvements in attention at follow-up. The follow-up periods varied

Table 3 Effect sizes of the theta/beta-based neurofeedback training compared to different treatments

Comparison condition	Studies	Hedges' g	Standard Error	Variance	Lower limit	Upper limit	Z-value	p value
WL	Bluschke et al. [30]	0.17	0.42	0.18	− 0.65	0.99	0.40	0.69
Physical activity	Geladé et al. [52]	0.01	0.25	0.06	− 0.48	0.50	0.04	0.97
	Rezaei et al. [79]	0.86	0.53	0.28	− 0.18	1.90	1.63	0.10
	Average effect size	0.31	0.41	0.17	− 0.49	1.10	0.76	0.45
Stimulant medication	Geladé et al. [52]	− 0.59	0.26	0.07	− 1.09	− 0.08	− 2.28	0.02
	González-Castro et al. [84]	0.56	0.25	0.06	0.08	1.05	2.27	0.02
	Meisel et al. [78]	− 0.35	0.41	0.17	− 1.15	0.46	− 0.84	0.40
	Sudnawa et al. [81]	− 0.70	0.32	0.10	− 1.33	− 0.07	− 2.17	0.03
	Average effect size	− 0.25	0.33	0.11	− 0.89	0.39	− 0.77	0.44
Other NF therapies	Arnold et al. [75]	0.21	0.17	0.03	− 0.14	0.55	1.17	0.24
	Mohagheghi et al. [85]	− 0.53	0.28	0.08	− 1.07	0.02	− 1.90	0.06
	Mohammadi et al. [86]	0.08	0.35	0.12	− 0.60	0.76	0.24	0.81
	Average effect size	− 0.06	0.24	0.06	− 0.52	0.41	− 0.24	0.81
Medication + NF	González-Castro et al. [84]	− 0.09	0.25	0.06	− 0.57	0.40	− 0.35	0.73
EMG-biofeedback	Bakhshayesh et al. [50]	0.64	0.34	0.12	− 0.03	1.31	1.87	0.06
	Maurizio et al. [55]	0.18	0.39	0.15	− 0.59	0.94	0.45	0.65
	Average effect size	0.44	0.26	0.07	− 0.07	0.94	1.71	0.09
No treatment	Bluschke et al. [82]	0.25	0.23	0.05	− 0.20	0.69	1.07	0.28
	González-Castro et al. [84]	1.33	0.27	0.07	0.80	1.86	4.94	0.00
	Rezaei et al. [79]	2.78	0.78	0.60	1.26	4.30	3.58	0.00
	Average effect size	1.25	0.57	0.32	0.14	2.36	2.20	0.03

WL, waitlist; NF, neurofeedback

from 3 to 20 weeks [mean (SD) = 9.88 (3.25)]. The random effects meta-analysis of long-term within-group effect sizes for pre-treatment and follow-up comparisons ranged from 0.56 to 1.11, the pooled effect size was 0.87 (95% CI [0.58, 1.16]) (Fig. 3). The Trim-and-Fill method showed that no studies would need to fall to the right of the mean and two studies would need to fall to the left of the mean to make the plot symmetrical. The random effects model for the adjusted pooled effect size revealed a Hedges' g = 1.07 (95% CI [0.71, 1.43]). The Egger's regression intercept was not significant (intercept = − 1.49, p = 0.47).

Effects of Measurement Tools

To evaluate if the improvements in attention in the reviewed studies were influenced by the types of measures used, the effect sizes for neuropsychological/behavioural measures and rating scales were computed separately. Six [50, 52, 79, 84–87] out of the 12 included studies used neuropsychological/behavioural tests to measure attention. The effect sizes (Hedges' g) for Pre- and Post-treatment comparisons ranged between—0.38 and 1.45, the pooled effect size was 0.41 (95% CI [− 0.06, 0.89]). All except one study [85] showed the effect was in favour of Post-treatment. The effect sizes (Hedges' g) for between-group comparisons ranged from—0.28 to 1.47, the pooled effect size was 0.33 (95% CI [− 0.11, 0.74]). Three out of six studies [50, 79, 84] had the effect in favour of NF training. The effect sizes (Hedges' g) for long-term effects based on two studies were − 0.50 and 0.24, the pooled effect size was—0.12 (95% CI [− 0.84, 0.61]. The effect of one study [52] was in favour of Post-treatment.

For the 11 studies used parent- or teacher-rating or self-report to measure attention [30, 50, 52, 55, 75, 78, 81, 82, 84–86], the effect sizes (Hedges' g) for Pre- and Post-treatment comparisons ranged from 0.33 to 2.75, the pooled effect size was 0.72 (95% CI [0.44, 0.99]). All studies had the effect in favour of Post-treatment. The effect sizes (Hedges' g) for between-group comparisons ranged from—1.01 to 0.58, the pooled effect size was—0.02 (95% CI [− 0.34, 0.31]). Four studies [52, 78, 81, 85] showed an effect in favour of the control condition. The effect sizes (Hedges' g) for long-term effects based on two studies were 0.89 and 2.71, the pooled effect size was 1.25 (95% CI [0.68, 1.81]).

Effects of Study Design

To evaluate whether the study design has an impact on the results, the effect sizes of RCTs (n = 7) [50, 52, 55, 75, 78, 79, 81], and non-RCTs (n = 5) [30, 82, 84–86] were computed. The Pre-and Post-treatment effect sizes for RCTs ranged from 0.24 to 1.45, the pooled effect size was 0.75 (95% CI [0.45, 1.05]). The between-group effect sizes ranged from—0.70 to 1.47, the pooled effect size was 0.12 (95% CI [− 0.31, 0.55]). And the long-term effect size for RCTs ranged from 0.56 to 1.11, the pooled effect size was 0.90 (95% CI [0.55, 1.25]). For non-RCTs, the Pre-and Post-treatment effect sizes ranged from 0.23 to 0.83, the pooled effect size was 0.51 (95% CI [0.24, 0.78]). The between-group effect sizes ranged from—0.53 to 0.56, the pooled effect size was 0.14 (95% CI [− 0.27, 0.55]). And the long-term effect size was 0.57 (95% CI [− 0.27, 1.41]).

Discussion

This systematic review and meta-analysis found that theta/beta waves NF training had both short-term and long-term benefits to attention problems in children with ADHD. Results also show that the magnitude of the training effects found in the present meta-analysis, medium within-group effects at Post-treatment and large within-group effects at Follow-up, were comparable to those reported in other meta-analytic studies on children [88] and adults with ADHD [58]. The benefits of theta/beta NF training were found to be sustainable and increased from Post-treatment to Follow-up in both the present meta-analysis and a previous meta-analysis [88]. The training effects continue to improve after the cessation of treatment is believed to be related to the underlying mechanisms of NF training. NF aims at training the brain to improve self-regulation by providing it with information (e.g., auditory tone or visual animation) about its electrical activities on the head [54]. It has been proposed that NF training is based on operant conditioning and procedural learning. Through learning mechanisms, regulation of own brain activities is learned and neuroplasticity is expected to take place during NF training, subsequently alteration of the mechanisms underlying cognitive processes and behaviors are expected to be observed [16]. Because learning and neuroplasticity take time to occur, training effects are thus more explicit at Follow-up than at Post-treatment.

The present meta-analysis also found that the between-group comparisons on attention problems showed a small effect at Post-treatment. This finding was in line with a previous meta-analysis on children with ADHD [88]. When further examining the between-group effects with regard to the control conditions, a large effect size for non-active control was found in this meta-analysis, but a medium effect was found in a previous meta-analysis [88]. The inconsistent findings across meta-analyses could reflect that the present meta-analysis was focused on the effects of theta/beta waves NF training only, while the previous meta-analysis has also included different NF protocols such as SCP and SMR. Theta/beta NF training targets the reduction of theta waves associated with an inattentive state and an increase of beta waves associated with an attentive state, it focuses on the regulation of attention [54]. Besides, literature shows that the electrophysiological characteristics commonly observed in children with ADHD are high theta-to-beta ratios such as high theta power and/or low beta power [48]. Because theta/beta waves NF training directly targets at these issues in children with ADHD, a greater training effects may be expected. SCP training aims at decreasing contingent negative variation (CNV) amplitude in children with ADHD. CNV is a negative shift of EEG in the cortical brain region, which indicates a reduction of the excitation threshold of cortical cells and are thought to be related to cognitive preparation. Reduced cortical negativity is thought to be associated with the inattention and hyperactivity/impulsivity in children with ADHD [54]. Sensorimotor rhythm (SMR) is a specific type of low beta activity observed in the sensorimotor cortex. SMR amplitude increases when the corresponding sensorimotor area is inactive and decreases when the corresponding sensorimotor area is under activation. SMR training targets the hyperkinetic behaviors of children with ADHD [54]. Among these three NF training protocols, theta/beta NF training focuses on the regulation of attention which has the most benefits for the attention problems of children with ADHD. Thus, larger training effects were found in the present meta-analysis than the previous one. Moreover, the training effect for non-active control in the present meta-analysis was based on one study only, while the same effect was based on seven studies in the previous meta-analysis. The large effect found in this meta-analysis could reveal the characteristics of that study only but not the “true” effect. In order to verify this finding, more studies on examining the effects of theta/beta waves NF training are required.

Apart from the large effect found when compared to non-active control, the present meta-analysis also found that theta/beta waves NF training had a greater effect size for attention problems than waitlist control, physical activities such as Yoga, and sham NF, which were consistent with a previous meta-analysis [57]. Although this finding shows that theta/beta waves NF training is superior to non-active control, waitlist group, and sham NF, it is noteworthy that there are also limitations of using theta/beta waves NF training for children with attention problems. Theta/beta waves NF training requires children to focus attention to the feedback of their own brain activities. Through regular practice, children exercise their ability to ignore distraction and focus for longer period of time. In order words, the basic requirement for NF training is children are able to pay attention on a feedback (e.g., an auditory tone or a visual animation) and sustain their attention on it for a period of time. It could be a challenge to children to learn how to focus their attention on the feedback during NF training if they have attention deficits, leading to frustration and subsequently a negative impact on the treatment efficacy. Findings of the present meta-analysis also showed that theta/beta waves NF training had a smaller effect size than stimulant medication, which echoed the findings of a past meta-analysis [89]. Given the effect of theta/beta waves NF training is smaller than that of stimulant medication, NF training could be considered as an intervention choice for those children who are non-responders to stimulant medication or for those children whose parents are worried about the side effects of medications.

When examining the influences of measurement tools on the effect of NF training, significant training effects were found in within-group analyses when either neuropsychological/behavioural measures or rating scales were used to measure attention. However, the overall effect size of studies using neuropsychological/behavioural measures was smaller than that of studies using rating scales. It is possible that the effect sizes for parent- and teacher-rating scale are inflated due to the potential bias arising from the treatment expectations from parents and teachers as they usually know which treatment that the child was receiving. Although parent- and teacher-ratings are comparatively more subjective to behavioural tests, both parent and teacher ratings have been considered as valid measures for evaluating clinical efficacy [90]. Thus, in order to avoid the potential inflation of effect size caused by the bias of raters, both behavioural tests and rating scales should be used as outcome measures in future studies.

For neuropsychological/behavioural testing, the averaged within-group effects were 0.41(95% CI [− 0.06, 0.89]) for Pre- and Post-treatment comparisons, and—0.12 (95% CI [− 0.84, 0.61]) for Pre-treatment and Follow-up comparisons. Apparently, these findings showed that the effects of NF training were not sustainable after the cessation of training as the effect size for Pre-treatment and Follow-up comparison was in favour of Pre-treatment. However, when the effects of rating scales were examined, the averaged within-group effect was 0.72 (95% CI [0.44, 0.99]) at Post-treatment and 1.25 (95% CI [0.68, 1.81]) at Follow-up, suggesting a continuous improvement after training. The discrepancy in findings could be explained by the reason that the Follow-up effect yielded from neuropsychological/behavioural testing was based on two studies only, they may not truly reflect the long-term effect of NF.

Both RCTs and non-RCTs study designs showed significant effect size in within-group and between-group analyses, but the effect sizes of RCTs were generally larger than that of non-RCTs. In the present meta-analysis, 10 out of 13 RCTs were of good-to-excellent methodological quality (majorities of RCTs were of high methodological quality) while three out of six non-RCTs were of high quality, it is possible that studies of design with low methodological quality may hamper the effects of NF training.

Limitations

The present meta-analysis has some limitations. First, the two trials with serious risk of bias [30, 86] were also included in the present meta-analysis in order to improve the statistical power. Because features of the study design of these two trials may cause misleading findings and affect the overall training effects, cautions should be taken when interpreting the results. Second, between-group analyses, theta/beta waves NF training were compared to seven different types of control conditions in 12 included studies, for some comparisons, there was only one study involved. In view of the great diversity of control conditions, generalizations of the results are limited by the small number of studies involved in each between-group comparison. In addition, due to the great variation of control conditions, the effects of theta/beta waves NF training to different comparators may cancel out each other, leading to a pooled effect size which is smaller than the true effect size of a specific control condition. Thus, in the future, it is better to focus on examining the effect of theta/beta waves NF training to a specific comparator in order to have a better understanding of its clinical efficacy. Third, Arns et al. [91] mentioned that teacher-rating becomes less reliable for rating children's behaviours after 12 years of age because more teachers are involved in children's education and in shorter period of time beyond this age [87]. When examining the influences of parent- and teacher-rating to the effect of theta/beta waves NF training on attention problems in children with ADHD, the effects were computed based on both parent- and teacher-rating instead of computing the effects of parent-rating and teacher-rating separately. This may affect the reliability of the training effects in some studies in this meta-analysis. Finally, although theta/beta waves NF training was found to have smaller effect than stimulant medication, it remains unclear if theta/beta waves NF training can be used as a standalone intervention for ADHD. In order to address this issue, the neuromechanism underlying the effects of theta/beta waves NF training should be examined and compared to that of stimulant medication in future studies.

Conclusions

The findings of the present systematic review and meta-analysis show that theta/beta waves neurofeedback training is effective for improving attention in children with ADHD. Therefore, theta/beta waves NF training can be considered an evidence-based nonpharmacological treatment choice for ADHD. Although well-designed studies provide support to the effectiveness of neurofeedback training, the optimal intervention protocols remain unknown. Moreover, theta/

beta waves NF training does not have a treatment effect superior to that of stimulant medication, a gold standard treatment for ADHD, cautions should be taken when considering it as a standalone treatment. In the future, RCTs that explore the adjutant therapeutic effects of NF training and to investigate the neuromechanism underlying both NF training and stimulant medication could improve our knowledge on the effects of theta/beta waves NF training on children with ADHD.

Summary

Neurofeedback training is a common treatment option for attention deficit hyperactivity disorder (ADHD). Given theta/beta-based neurofeedback training targets at the electrophysiological characteristics (high theta-to-beta ratios) of children with ADHD, benefits for attention may be expected. This systematic review and meta-analysis examined the effects of theta/beta-based NF training by considering the control conditions and the types of measures used to assess attention. Five databases included PsycINFO, PubMed, ScienceDirect, Scopus, and Web of Science were searched. Within-group and between-group effect sizes (Hedges' g) were calculated and analyzed. Nineteen studies (13 RCTs and 6 non-RCTs) met selection criteria for systematic review, 12 of them (7 RCTs and 5 non-RCTs) were included in meta-analysis. Within-group effects on attention were medium (pooled Hedges' g = 0.65) at Post-treatment and large (pooled Hedges' g = 0.87) at Follow-up. Between-group analyses revealed that theta/beta-based neurofeedback training had larger effect than no treatment (Hedges' g = 1.25), waitlist control (Hedges' g = 0.17), physical activities (Hedges' g = 0.31), and sham NF (Hedges' g = 0.21). However, the effect of theta/beta-based neurofeedback training was not superior to that of stimulant medication (Hedges' g = − 0.25). Subgroup analyses showed that between-group effects for neuropsychological/behavioral tests were smaller than the effects for rating scales. Results of this review showed that theta/beta-based neurofeedback training has benefits for attention in children with ADHD, due to the small number of studies reviewed, cautions should be taken when interpreting the findings.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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