Efficacy of neurofeedback training for improving attentional performance in healthy adults: A systematic review and meta-analysis

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Declarations of interest

None

Abstract

This systematic review and meta-analysis examined the effects of neurofeedback training (NFT) on attentional performance in healthy adults. Six databases (PubMed, Scopus, Web of Science, PsycInfo, JDreamIII, and Ichu-shi) were searched up to June 2022 for randomized controlled trials (RCTs) comparing attentional performance following NFT to a control group. Risk of bias was determined using the Cochrane Collaboration's tool. We identified 41 RCTs for qualitative synthesis and 15 RCTs without high risk of bias (including 569 participants) for meta-analysis using a random-effects model. The overall effect of NFT on attentional performance was significant (standardized mean difference = 0.27, 95% confidence interval = 0.10–0.44). However, approximately half of the studies did not compare its effects with sham-NFT, and no significant pooled effect of NFT was found in the studies compared to a sham-NFT group. Furthermore, subgroup analyses revealed variable effects on individual attentional performance subsets (executive function, spatial orientation, and arousal). Future large-scale sham-controlled RCTs are needed to confirm the efficacy of NFT for improving attentional performance.

Keywords

attentional performance, spatial orientation, executive function, arousal, EEG, neurofeedback training

1. Introduction

Attention is essential for cognitive functions and complex behaviors. It helps select contextually critical information, ignore irrelevant information, and maintain or control task-relevant goals, thoughts, and emotions. Previous studies have identified multiple subtypes of attention and categorized them from multiple aspects (Egeth and Kahneman, 1975; Pashler and Sutherland, 1998; Wickens, 2002). For instance, Posner and colleagues defined three distinct subtypes of attention: executive function, spatial orienting, and arousal (Petersen and Posner, 2012). Executive function establishes and maintains task-relevant goals while preventing interference and conflicts. Spatial orienting localizes a target and prioritizes processing toward that target. This can be achieved regardless of foveal fixation if the target is detected by the visual domain. Arousal maintains the optimal level of alertness to effectively perceive high priority signals and prepare an appropriate response. Posner and colleagues also argued that these three subtypes are mediated by largely independent brain networks (Fan et al., 2002; Posner and Petersen, 1990). Given the necessity of attention for cognitive processes, improving attentional functions would have broad benefits in daily life, including enhanced work performance and safety.

Neurofeedback training (NFT) is a method designed to self-modulate brain activity and thereby exert control over various physiological and cognitive processes for improved health and daily function, including attentional performance (Gruzelier, 2014). For example, NFT aimed at increasing sensorimotor rhythm (SMR) power has been proposed to enhance general attention (Egner and Gruzelier, 2004a), while enhancing alpha power may facilitate the inhibition of irrelevant stimuli, thereby enhancing executive function (Hanslmayr et al., 2005). Several reports have also implied the relationship between attentional performance and frontal theta (Cavanagh et al., 2012) or low beta power (Egner and Gruzelier, 2004a). Furthermore, two recent meta-analyses (Lambez et al., 2020; Van Doren et al., 2019) have shown that NFT

can mitigate inattention and hyperactivity among patients with attention-deficit / hyperactivity disorder (ADHD).

However, it is unclear whether NFT can further enhance attentional performance in healthy adults rather than alleviate the attentional disruption in clinical populations. The results of studies on patients with ADHD cannot be directly applicable to the healthy population given that psychostimulants used to treat ADHD, such as methylphenidate, may affect neural plasticity (Korchounov and Ziemann, 2011; Ridding and Ziemann, 2010). Therefore, it is essential to investigate whether NFT is an effective approach for improving attentional performance among healthy adults. This knowledge is crucial for determining the applicability of NFT in improving their performances at work (Mazur et al., 2017; Ros et al., 2009) and sports (de Brito et al., 2022).

Here, we conducted a systematic review of NFT effects on attentional performance among healthy adults. A meta-analysis was also performed to quantitatively evaluate the NFT effect in enhancing attentional performance and to clarify the NFT effect on each subtype of attentional performance, with each type of NFT protocol (e.g., enhancing SMR or alpha power), and over each type of control condition. The present study differs from previous two systematic reviews on the effects of NFT on attentional performance (Da Silva and De Souza, 2021) and executive function (Da Silva and De Souza, 2021; Viviani and Vallesi, 2021) in healthy adults because of the following reasons. First, neither conducted a meta-analysis. Second, the effects of NFT on the individual subsets of attentional performance (executive function, spatial orienting, and arousal) have not been examined. Finally, control conditions have varied among studies, so it is worthwhile to establish the superiority of NFT for attentional performance improvement over different control conditions: sham-NFT, general training methods such as video game play (Nouchi et al., 2021) or meditation (Egner and Gruzelier, 2004b; Nouchi et al., 2021), and no intervention. In particular, comparing the efficacy of NFT to sham-NFT is

crucial for clarifying the effect specific to modulating the targeted brain activity (Schönenberg et al., 2017), while comparisons with general training methods are essential for demonstrating superiority over other alternatives.

2. Materials and methods

This systematic review and meta-analysis were conducted according to Chapter 4 of the Minds manual for clinical practice guideline development (Minds Manual Developing Committee, 2021). This study was not pre-registered.

2.1. Database search

Two authors independently searched for English and Japanese articles investigating NFT effects on attentional performance using the English databases (PubMed [IK and HN], Scopus [IK and HN], Web of Science [IK and HN], and APA PsycInfo [RiO and JK]), the Japanese database for scientific studies (JDreamIII [RiO and JK]), and the Japanese database for medical trials (Ichu-shi [RiO and JK]). Searches of PubMed and Web of Science were conducted in May 2022, while searches of all other databases were conducted in June 2022. Search strings included both attention-related AND neurofeedback-related terms as well as NOT terms related to clinical or animal studies. Attention-related terms were “attention*” OR “wakefulness” OR “executive function” while NFT-related terms were “neurofeedback” OR “neuro feedback” OR “brain machine interface” OR “brain–computer interface” OR (“feedback” AND EEG OR electroencephalogra*). To further eliminate clinical and animal studies, we excluded if the following keywords existed in the title: (ADHD OR disorder* OR deficit* OR patient* OR rehabilitation OR epilep* OR disease* OR depress* OR injur* OR damage*) OR (animal* OR rodent* OR monkey* OR rat OR rats OR macaque*). These searches were conducted in English using PubMed, Scopus, Web of Sciences, and APA PsycInfo, whereas JDreamIII and Ichu-shi were searched using equivalent Japanese terms (See Supplementary Table 1 for the exact search queries used for each database).

2.2. Screening procedures

We then screened the articles retrieved from all databases in two phases. First, we removed obviously unrelated articles based on title and abstract contents, and then inspected the remaining full articles for eligibility. During this second phase of screening, the following data were extracted and considered for eligibility: study design, participant demographics, intervention type, control condition, and outcome measures related to attentional performance. We divided the articles into three groups for each phase, and each group was screened independently by two authors (IK and HN, HN and RyO, or RyO and IK). In case of disagreement between the two authors, another author investigated the article (RyO for IK and HN, IK for HN and RyO, HN for RyO and IK) to reach a consensus. If the three authors still disagreed on eligibility, the other authors inspected the articles, and all six authors reached agreement through further discussion.

Studies were included in the qualitative synthesis based on the following eligibility criteria: (1) Populations: healthy adults 18–64 years of age; (2) Intervention: NFT using a non-invasive measure of brain activity to improve attentional performance; (3) Comparison: any type of control condition; (4) Outcome: objective or subjective reports reflecting attentional performance measured to assess the effect of NFT; (5) Study design: randomized control trial (RCT); (6) Source: Published in a scholarly peer-reviewed journal and written in English or Japanese.

From these eligible studies, we excluded those from subsequent meta-analyses if (1) data were not available to calculate the effect size between experimental and control conditions or (2) the study was judged as having a high risk of bias (See Section 2.4 for detailed definitions of risk of bias).

2.3. Data extraction

Two authors (IK and HN) extracted the data from each eligible article for qualitative synthesis and meta-analysis. For qualitative synthesis, the details extracted were participant demographics, intervention, control condition, outcome measures of attentional performance, and adverse events if any. The attentional outcome measures in each study were further classified as follows according to the targeted attentional performance subset: executive function (e.g., flanker effect, Simon effect, Navon task, psychological refractory period effect, dual-task performance, task switching, working memory span task, operation span task, paced auditory serial attention test, trail making test, dichotic listening test, n-back task), spatial orienting (e.g., spatial cueing, visual search, attentional blink, change detection, priming, multiple object tracking, subitizing), and arousal (e.g., sustained attention to a response task, continuous performance task, mind wandering). Two authors (RiO and JK) independently inspected the measured subsets. If judgements were inconsistent, four authors (IK, HN, RiO, and JK) discussed the classification until an agreement was reached.

Outcome measures of attentional performance after the last NFT session were further extracted for the meta-analysis. We regarded every experiment in each paper as a single trial, and the following values were extracted from each for meta-analysis: mean and standard deviation of the attentional outcome measures after the last NFT session and the number of participants in the experimental and control groups. From either these values or t-values, the standardized mean difference (SMD), was calculated. If neither SMDs nor t-values were available, we contacted the corresponding author of the study for the required data. Finally, we reversed the sign of SMD if a lower value reflected higher attentional performance (e.g., reaction time, tiredness, or sleepiness) for consistency across studies so that higher SMD consistently indicates that NFT increases attentional performance compared to controls.

2.4. Risk of bias assessment

Two authors (IK and HN) assessed the risk of bias for all the studies whose SMDs are available using the Cochrane Collaboration's tool (Higgins et al., 2011). This tool classifies risk of bias as high, unclear, or low on six domains: selection bias, performance bias, detection bias, attrition bias, reporting bias, and others (including conflict of interest, early trial termination, and incorrect sample size determination or statistical methods). Each domain was scored two points for high, one for unclear, or zero for low, and then points were summed to yield an overall risk score. We then classified overall risk as high if the score was more than seven or more than two domains were high, as low if total score was less than five and less than two domains were high, or as moderate in other cases. Individual studies judged as low or moderate overall risk of bias were included in the meta-analyses. A summary table on risk of bias evaluation was constructed using *robvis* (https://mcguinlu.shinyapps.io/robvis/; McGuinness and Higgins, 2021).

2.5. Statistics

The basic characteristics of studies that passed the second screening were tabulated, including participant demographics, adverse events, targeted brain location and activity for NFT, type of control condition, and subset of attentional performance investigated (executive function, spatial orienting, and/or arousal) (Table 1). We then performed a standard pairwise meta-analysis using a random-effects model. All results on the same outcome and population were pooled into a single dataset. Since several studies assessed multiple metrics for a single intervention, we applied a robust variance estimation method (Fisher and Tipton, 2015) to cope with multiple interdependent effect sizes within each study. Publication bias was visualized using a funnel plot and evaluated using Begg's and Egger's tests (with $P < 0.1$ on both tests considered significant). Heterogeneity across studies was assessed using Cochran's Q and the I^2 statistic. We also performed an additional meta-analysis using a fixed-effect model and without excluding the studies with high risk of bias to confirm the robustness of the results.

To clarify the dose–response relationship, a meta-regression analysis was applied to the total duration of NFT and the effect size in each study. Here, we defined the total duration of NFT as the duration of each session × the number of sessions. If the duration of NFT in each session was described as a range (e.g., 30–40 min), the mid-value was used (e.g., 35 min).We conducted additional subgroup meta-analyses to clarify the efficacy of NFT for each subset of attentional performance (executive function, spatial orienting, or arousal), type of outcome measure (subjective or objective), type of brain activity targeted for intervention (SMR or alpha power), and type of control (sham-NFT, general training, or no intervention). All statistical analyses were performed using *metafor* ver. 3.4.0 (Viechtbauer, 2010), *meta* ver. 5.5.0 (Balduzzi et al., 2019), and *clubSandwich* ver. 0.5.8 in R ver. 4.1.2 (https://www.r-project.org/).

3. Results

3.1. Search results

The literature review process is illustrated in Figure 1. We retrieved 3,337 articles from six databases using the indicated search strings, of which 3,159 were excluded as irrelevant based on the title or abstract. The remaining 178 articles were then screened for eligibility by full-text assessment, of which 137 were excluded for the following reasons: study of a clinical population (1 article), age of subjects (17 articles), article type (27 articles), no NFT (10 articles), no control conditions (22 articles), no outcome measure for attentional performance (38 articles), and non-RCT (22 articles). The remaining 41 articles were retained for qualitative synthesis and 15 were further included in meta-analyses. Reasons for exclusion from the meta-analyses were insufficient data reported to calculate effect sizes (24 articles) and high overall risk of bias (2 articles).

3.2. Study and sample characteristics

Table 1 summarizes the main characteristics of all studies included in the qualitative synthesis. All were published between 1991 and 2021 (Figure 2A), with more than half appearing after 2013. Thirteen studies examined executive function alone, five examined spatial orienting alone, and seven examined arousal alone, while three examined both executive function and spatial orienting, six examined both executive function and arousal, four examined spatial orienting and arousal, and three examined all three subsets of attention (Figure 2B). Among studies of EEG-based NFT, the vertex (Cz) was the most frequently applied electrode location, followed by the right frontal (F4), midline frontal (Fz), central (C3, C4), and midline parietal (Pz) locations (Figure 2C). Thirty-four studies used EEG, four fMRI, two near-infrared spectroscopy (NIRS), and one magnetoencephalography (MEG). The EEG-based studies targeted alpha, beta, SMR, gamma, and/or theta powers (Figure 2D). Most studies targeted alpha power with single band (five out of six studies), while beta and SMR powers

were more often targeted with multiple bands (beta power: five out of seven studies; SMR power: six out of 10 studies) than with single band. Twenty-six studies compared NFT to sham-NFT, 12 studies to no intervention, 4 studies to general training, and 2 to biofeedback without EEG. The control condition in one study was unknown.

3.3. Adverse events

Only two of 41 studies reported the presence of absence of adverse events, and neither reported any such events during or after NFT.

3.4. Risk of bias assessment

Of the 17 RCTs evaluated, overall risk of bias was high in 2, moderate in 13, and low in 2 ("Overall" column in Figure 3). Only three studies explicitly described the random sequence generation method and were evaluated as low risk for selection bias (column D1 in Figure 3), while the others did not describe the allocation method and were judged as unclear risk. Only one study described the allocation concealment, which was also judged as low risk for selection bias (column D2 in Figure 3). Two studies were single-blinded or unblinded and thus judged as high risk of performance bias (column D3 in Figure 3), five were double-blinded and deemed low risk, and ten did not describe the blinding procedure and were deemed as unclear risk of performance bias. Most studies did not explicitly mention the blindness of the evaluator, so the risk of detection bias was unclear (column D4 in Figure 3). Further, one study was explicitly unblinded. Thirteen studies were judged as low risk of attrition bias (Column D5 in Figure 3), while four studies were judged as high risk since the drop-out rate was more than 10% or intention-to-treat protocols were violated. Fifteen studies had unclear reporting bias as none performed pre-registration (column D6), one study was judged low risk because data were collected according to the pre-registered protocol, and one was judged high risk because the reported items were incomplete without any explicit reason. Finally, seven studies were rated

high risk of other biases due to conflicts of interest (seven studies), early trial termination (one study), or inadequate statistical methods (e.g., no considerations for multiple comparisons) (three studies). The other ten studies were rated unclear risk due to the lack of information any on these items. Two studies with high overall risk of bias were excluded from the subsequent meta-analysis.

3.5. General effects of NFT on attentional performance

A total of 16 trials (n = 569) from 15 published studies were included in the primary meta-analysis. NFT enhanced attentional performance with small effect size (SMD = 0.27, 95% confidence interval (CI) = 0.10–0.45, t = 6.68, P = 0.0076; Figure 5A; See Supplementary Figure 1 for the forest plot). This result was relatively robust as it was not severely altered without removing the two studies with high overall risk of bias (SMD = 0.25, 95% CI = 0.10–0.41, t = 3.80, P = 0.0054). Repeating the meta-analysis using a fixed-effects model (rather than the original random-effects model) also did not severely alter the effect size (SMD = 0.27, 95% CI = 0.10–0.44, t = 3.77, P = 0.0076), indicating that outliers did not strongly influence the result. There was no significant heterogeneity across the trials (Q = 52.5, P = 0.93, I^2 = 0%) and no significant publication bias according to the funnel plot (Figure 4), Begg's test (z = 1.68. P = 0.093), and Egger's test (t = 1.24, P = 0.22). Meta-regression analysis revealed no significant relationship between effect size and the total duration of NFT (12 trials; beta = 0.0003, 95% CI = −0.0006–0.0012, t = 1.04, P = 0.37) or the number of NFT sessions (15 trials; beta = 0.013, 95% CI = −0.013–0.038, t =1.58, P = 0.21).

3.6. Subgroup meta-analyses

We performed subgroup meta-analyses to evaluate the effect of NFT on each attentional performance subtype (Figure 5B) and type of outcome measure (objective or subjective; Figure 5C), targeted brain activity by NFT (Figure 5D), and type of control condition (Figure 5E). The

estimated effect on executive function (12 trials) was small (SMD = 0.27, 95% CI = 0.10–0.43, t = 4.06, P = 0.0088; heterogeneity: Q = 45.8, P = 0.72, I^2 = 0%) and that on spatial orienting (six trials) was intermediate (SMD = 0.50, 95% CI = 0.034–0.97, t = 2.96, P = 0.041; heterogeneity: Q = 3.12, P = 0.87, I^2 = 0%), while that on arousal (seven trials) was not significant (SMD = 0.25, 95% CI = −0.18–0.68, t = 1.58, P = 0.18; heterogeneity: Q = 4.99, P = 0.96, I^2 = 0%) (Figure 5B). However, there was no significant difference in NFT effect size among subtypes ($F_{3, 3.34}$ = 0.56, P = 0.68). Effect size was small regarding the 16 trials using objective measures (SMD = 0.33, 95% CI = 0.19–0.47, t = 5.71, P = 0.0014; heterogeneity: Q = 42.38, P = 0.94, I^2 = 0%), and not significant across the three trials using subjective measures (SMD = −0.046, 95% CI = −1.65–1.56, t = −0.22, P = 0.86; heterogeneity: Q = 6.61, P = 0.76, I^2 = 0%) (Figure 5C). The difference in NFT effect between types of outcome measures was not significant ($F_{1, 1.73}$ = 3.00, P = 0.24).

When intervention targets were considered separately, NFT demonstrated no significant effect on either alpha power (four trials, SMD = 0.24, 95% CI = −0.45–0.92, t = 1.57, P = 0.26; heterogeneity: Q = 16.3, P = 0.30, I^2 = 0%) or SMR power (six trials, SMD = 0.16, 95% CI = −0.58–0.90, t = 0.81, P = 0.49; heterogeneity: Q = 23.8, P = 0.25, I^2 = 14.7%). We did not evaluate the effect of NFT using other neuroimaging modalities because only one study used NIRS or fMRI.

Notably, NFT had no significant effect on overall attentional performance when compared to sham-NFT as the control condition (eight trials, SMD = 0.18, 95% CI = −0.18–0.53, t = 1.57, P = 0.21; heterogeneity: Q = 16.9, P = 0.98, I^2 = 0%) (Figure 5E), and also no significant effects on executive function (six trials; SMD = 0.20, 95% CI = −0.16–0.56, t = 2.08, P = 0.15), spatial orientation (two trials; SMD = 0.09, 95% CI = −2.81–3.00, t = 0.39, P = 0.76), or arousal (five trials; SMD = 0.22, 95% CI = −0.49–0.92, t = 1.05, P = 0.38) compared to sham-NFT. The effect of NFT was not significantly superior to general training (SMD = 0.29, 95% CI =

−1.05–1.63, t = 2.77, P = 0.22; heterogeneity: Q = 6.50, P = 0.44, I^2 = 0%). In contrast, NFT was superior to no intervention (SMD = 0.36, 95% CI = 0.003–0.73, t = 2.90, P = 0.049; heterogeneity: Q = 27.5, P = 0.44, I^2 = 0%). Again, there was no significant difference in effect among trials using different control conditions ($F_{2, 1.81}$ = 0.43, P = 0.70).

4. Discussion

The present study evaluated the effects of NFT on attentional performance using both a qualitative synthesis and meta-analysis of RCTs. We also performed subgroup meta-analyses to assess effects of NFT on specific subsets of attentional performance (executive function, spatial orienting, and arousal) as well as types of outcome measure (subjective or objective), targeted brain activity by NFT (alpha or SMR power), and control condition (sham-NFT, general training, and no intervention). A search of multiple English and Japanese databases identified 41 studies appropriate for qualitative synthesis and 16 trials (15 studies) acceptable for quantitative meta-analyses. The primary meta-analysis revealed a significant overall effect of NFT on attentional performance, and subgroup meta-analyses revealed significant effects on executive function and spatial orienting but not on arousal. However, neither the overall effect nor the effects on individual subsets were significant when compared to sham-NFT.

4.1 Significant overall NFT effect on attentional performance

Our meta-analysis of 15 studies indicated that NFT was superior to controls for enhancing overall attentional performance but with a small effect size (SMD = 0.27). The effect size was comparable to a previous meta-analysis of NFT efficacy for inattention (SMD = 0.38) and hyperactivity-impulsivity (SMD = 0.25) in patients with ADHD compared to controls (Van Doren et al., 2019). In contrast, Da Silva and De Souza reported a greater general mean effect of NFT on attentional performance compared to our results (*d'* = 0.61; Da Silva and De Souza, (2021)). These differences can be explained by the different indices between these two studies: Hedge's g used in the current study reflects a relatively small sample size (n = 8–25 in each study), whereas *d'* used in Da Silva and De Souza (2021) did not take into account the sample size.

We did not find a significant correlation between the NFT dose and efficacy. Lim and colleagues (2019) reported that at least 24 sessions are required for NFT to improve attentional

performance in patients with ADHD. Considering that only 3 out of 15 studies included in the meta-analysis conducted NFT for more than 24 sessions and the number of sessions of NFT ranges from 1 to 42 sessions, healthy adults might enhance attentional performance by a rather small number of sessions of NFT compared to patients with ADHD.

4.2 Variable NFT effect on each subgroup

The meta-analysis revealed significant effects of NFT on executive function and spatial orienting, in accord with previous systematic reviews concluding that NFT can enhance executive function (Da Silva and De Souza, 2021) and visual attention (Ordikhani-Seyedlar et al., 2016). However, in a review by Viviani and Vallesi (2021), only 16% of included studies reported that NFT improved executive function. These discrepancies may be explained by differences in the definition of success: our study focused on improvement of attentional performance measured by behavioral responses, whereas Viviani and Vallesi (2021) compared EEG changes to controls. By contrast, we found no significant effect of NFT on arousal compared to controls. We surmise that NFT may not be effective in improving arousal compared to in spatial orienting because the number of studies included in arousal was comparable to that in spatial orienting. Further studies are warranted to address why NFT can improve some attentional domains but not others.

While NFT produced an improvement in attentional performance in general, the meta-analysis revealed no significant effect on individual NFT protocols aimed to increase alpha or SMR power. This is surprising, at least in NFT targeted to increase SMR power, because SMR protocol has long been proposed to enhance attentional performance in healthy adults (Egner and Gruzelier, 2001). These non-significant effects of NFT on alpha and SMR power may be explained by the limited number of studies targeting each band power (four trials for alpha and six for SMR power). Another potential reason is that enhancement of a given band power may not necessarily improve all subsets of attentional performance. For example, several studies

have suggested that NFT protocols enhancing low beta and SMR power influence distinct aspects of attentional performance (Egner and Gruzelier, 2004a; 2004b).

The meta-analysis also revealed no significant effect of NFT on attentional performance when compared specifically to sham-NFT or to general training. Arina and colleagues (2017) reported that even sham-NFT can induce unspecific effect such as reducing tension or anxiety. This finding suggests that NFT effects specific to modulate certain EEG band power cannot be evaluated only by comparison with a non-intervention group. Nevertheless, only about half of the studies (21 out of 41) compared NFT to sham-NFT, and the details of the blinding protocols were unclear in most studies. As suggested in other systematic reviews on NFT (Da Silva and De Souza, 2021; Rogala et al., 2016), stringent triple-blind RCTs are needed to compare the effects of NFT to sham-NFT.

4.3 Limitations

The present study includes a potential limitation: we cannot assess the NFT effect on each neuroimaging modality. This is because just one study conducted NFT with NIRS (Nouchi et al., 2021) or fMRI (Kim et al., 2019) to enhance attentional performance. NIRS is a convenient tool to measure brain activity over EEG, and several studies suggest that NFT with NIRS is useful for the rehabilitation after stroke (Mihara et al., 2021; Rahman et al., 2020). NFT with fMRI is also a promising tool to modulate brain activity (Koizumi et al., 2020). Future studies are required to determine which neuroimaging modality can best improve attentional performance.

Aside from this limitation of the present study, a cautionary note is the incomplete information provided by several studies included in the current review. Specifically, of the 41 studies included, six did not specify the intervention period, six did not specify the number of sessions, and seven did not specify the daily intervention duration. Moreover, only two out of the 41 studies mentioned whether adverse events occurred. These data are critical for clarifying

the efficacy and safety of NFT as well as the optimal protocol for improving attentional performance. Future studies should comply with recent guidelines on the reporting of NFT studies (Ros et al., 2020).

In addition, only eight trials compared NFT to sham-NFT and only two trials to general training. Comparison with sham-NFT is essential for revealing the effect specific to modulating the targeted brain activity, while comparison with general training is crucial for clarifying which training (NFT or other) is more useful for enhancing attentional performance. More studies comparing the NFT effect with sham-NFT and with general training will be required to scientifically validate the NFT effect on attentional performance and the superiority of NFT over alternative methods.

4.4 Conclusion

From the currently available studies, NFT significantly enhances attentional performance compared to its control, without a significant dose–response relationship in healthy adults. Furthermore, NFT has been observed to significantly enhance executive function and spatial orientation, although whether NFT can significantly enhance arousal is still unknown. Unfortunately, approximately half of the studies included in this analysis did not compare NFT to sham-NFT, and the superiority of NFT over sham-NFT and alternative methods for enhancing attentional performance remains uncertain. To address these gaps, future multicenter RCTs with large sample sizes are required to compare NFT effect with sham-NFT in a stringent triple-blinded design, as well as with non-NFT training.

Data and code availability statement: Data and codes used in this study were shared in OSF (https://osf.io/5ze7v/).

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Figures and figure captions

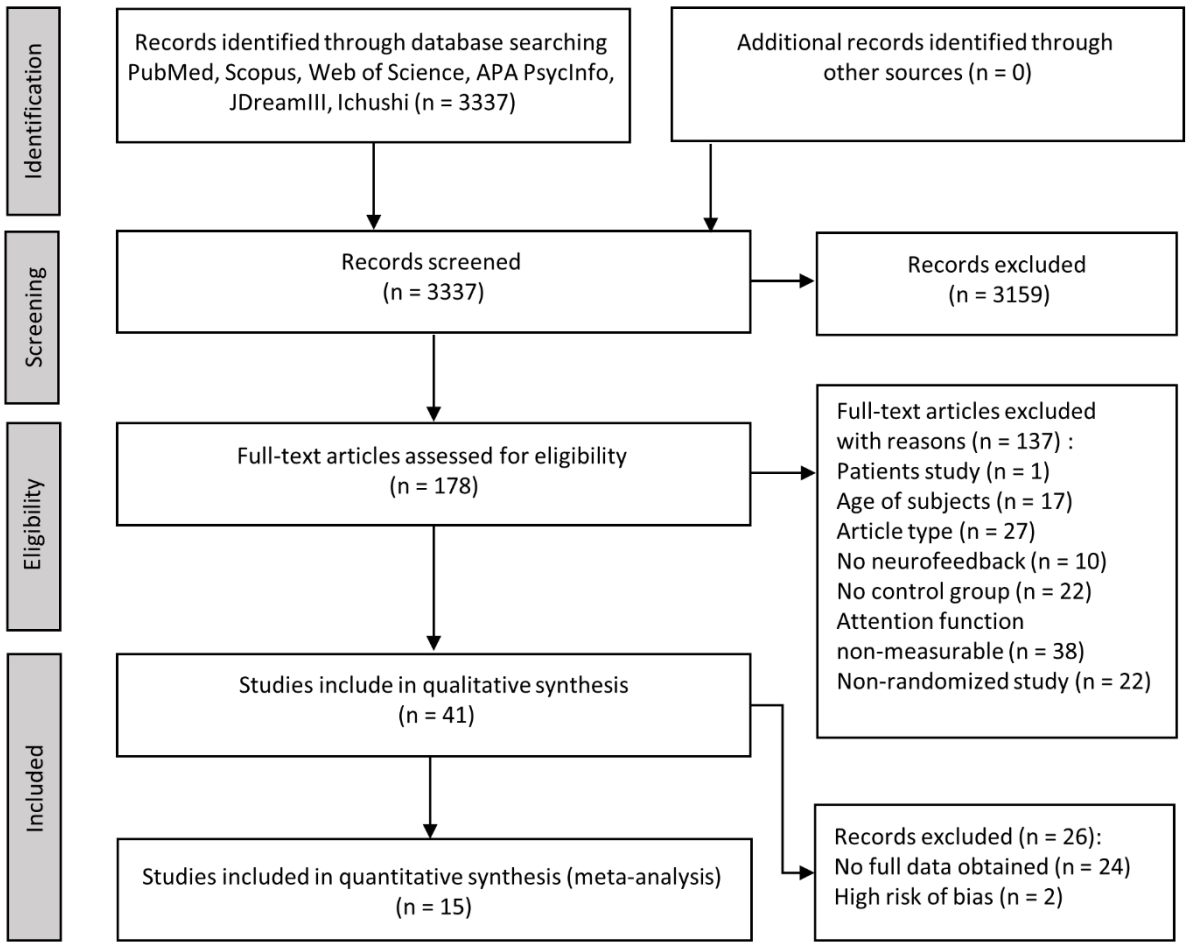

Figure 1. PRISMA flowchart of article search and inclusion.

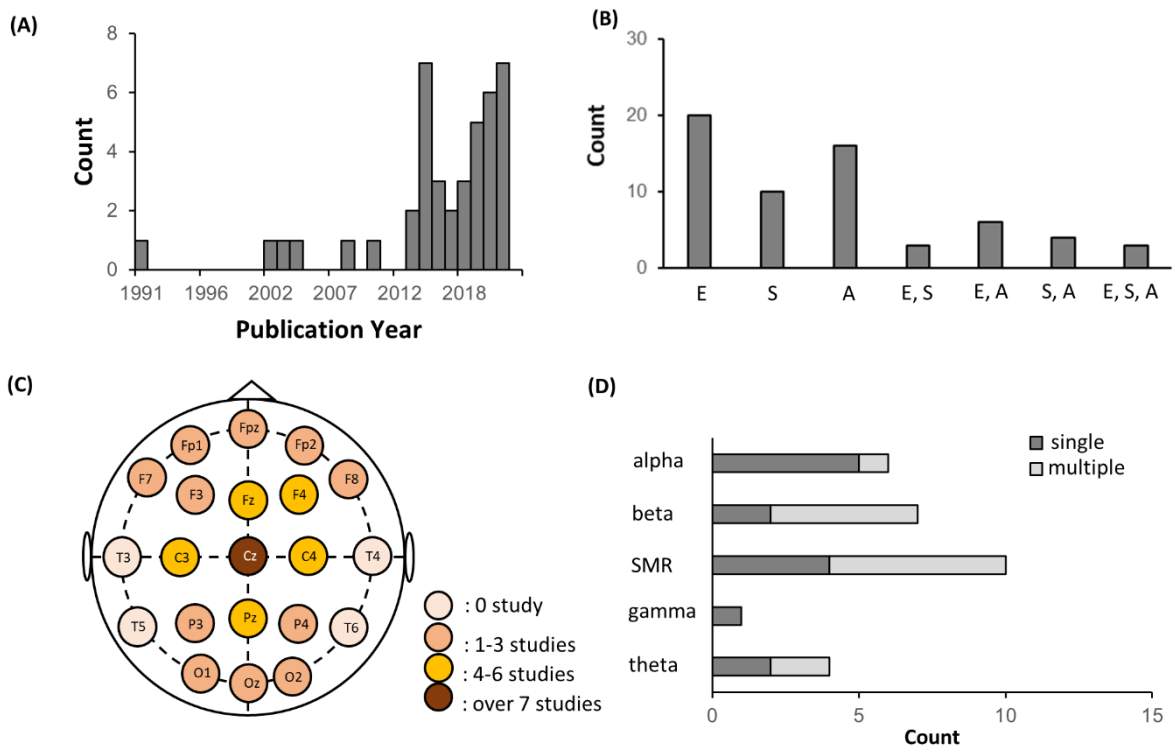

Figure 2. Qualitative assessment of NFT studies included in the analyses. (A) Histogram of publication year. (B) Attentional performance subset(s) targeted by NFT studies. (C) Channels recorded for EEG-based NFT. (D) Frequency band(s) targeted by EEG-based NFT study. Single and multiple denote that a band was targeted by intervening single-band or multiple-bands, respectively. Abbreviations: E, Executive function; S, Spatial orienting; A, Arousal; SMR, sensorimotor rhythm.

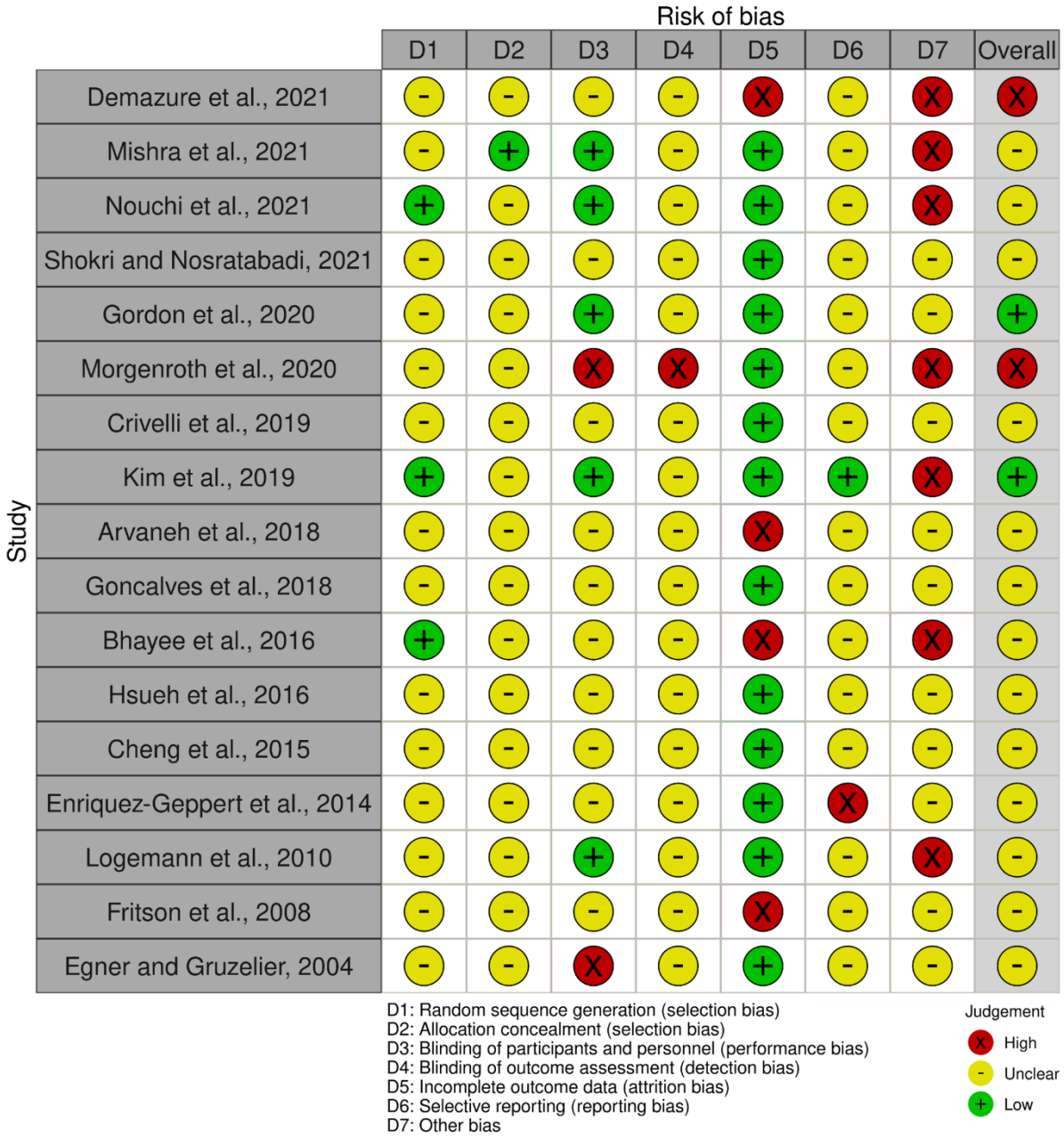

Figure 3. Risk of bias assessment for each study considered for the meta-analysis. The red, yellow, and green symbols in each domain column indicate high, unclear, and low risk of bias, respectively. In the overall column, red, yellow, and green indicate high, moderate, and low risk of bias, respectively. Based on this analysis, two studies (red in the overall column) were eliminated from the meta-analysis.

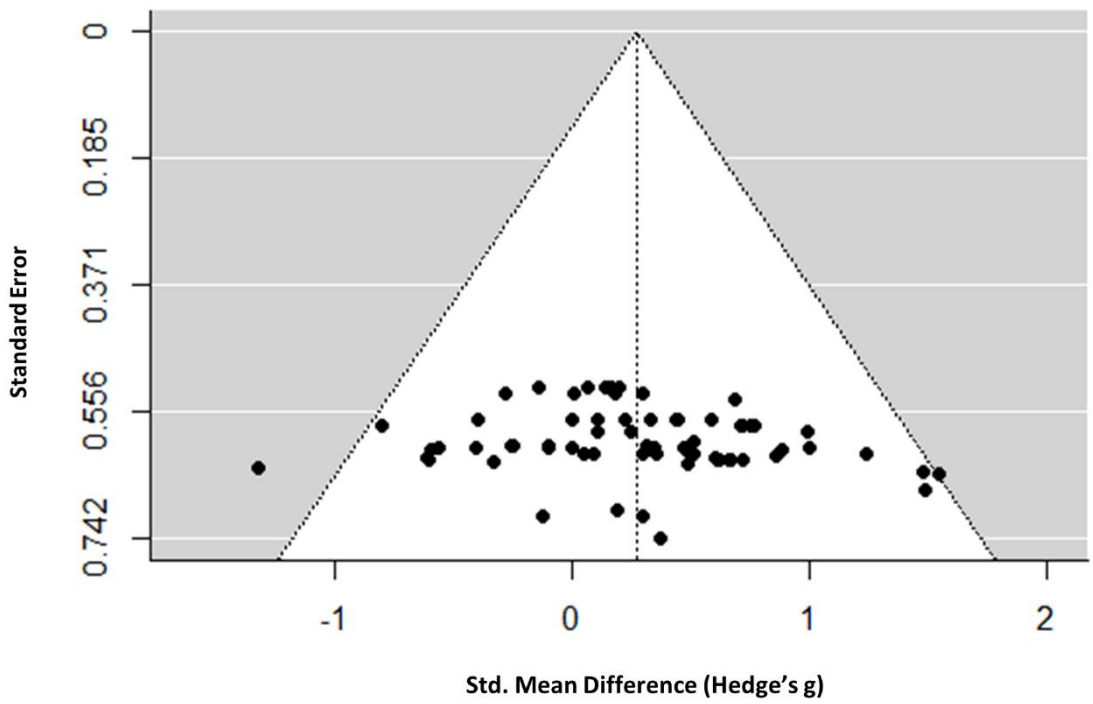

Figure 4. Funnel plot showing the standardized mean differences from all experimental results included in the meta-analysis. The relative symmetry suggests low risk of publication bias.

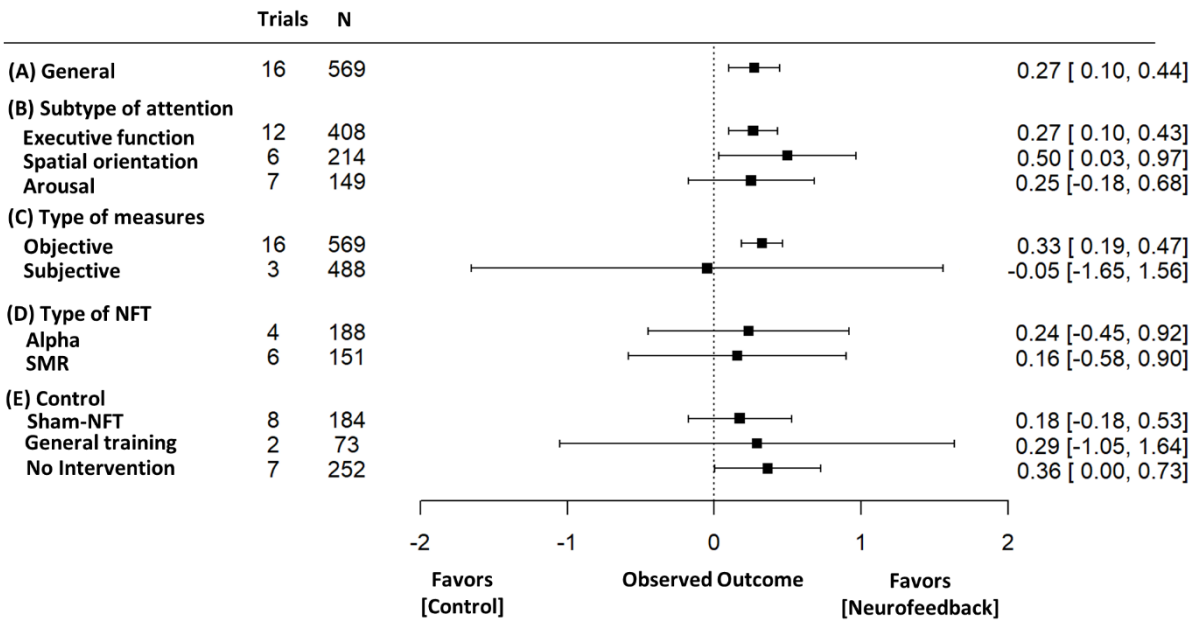

Figure 5. Forest plot of NFT efficacy for improving attentional performance. (A) Overall effect size estimate. (B–E) Estimated effect sizes for each subtype of attentional performance (B), type of outcome measures (C), type of brain activity targeted for NFT (D), and type of control (E). The squares are the means and error bars are the 95% confidence intervals of estimated effect sizes comparing NFT to control conditions.

Table 1. Experimental characteristics of the studies included in the qualitative synthesis. A qualitative summary was provided for each study according to the top-line items.

Study	Participant demographics	Adverse effects	Neuroimaging modality	Intervention(s) and EEG recording sites	Type of control condition	Type of feedback	Intervention period	Total intervention duration	Subtype of attentional performance
Cai et al., (2021)	Healthy adults	Not reported	EEG	Increase theta power (4–8 Hz); Decrease beta power (12–30 Hz) (Fp1, Fp2)	No intervention	Visual	5 weeks	more than 32 min × 5 sessions	E
Demazure et al., (2021)	Healthy adults	Not reported	EEG	Increase beta power (12–30 Hz) and decrease both theta power (4–8 Hz) and alpha power (8–12 Hz) (F3, F4, O1, O2)	No intervention	Visual	Unclear	90 min (number of sessions is unclear)	S + A
Kim et al., (2021)	Healthy adults	Not reported	EEG	Increase or decrease N1 and P1 power (Fz, FCz, FC1, FC2, Cz)	sham-NFT	Visual	4 weeks	60 min (number of sessions is unclear)	S
Mishra et al., (2021)	Healthy adults	Not reported	EEG	Decrease alpha frontal-sensory synchrony (8–12 Hz)	sham-NFT	Visual	3–5 weeks	40 min × 10 sessions	S + A

Study	Participant demographics	Adverse effects	Neuroimaging modality	Intervention(s) and EEG recording sites	Type of control condition	Type of feedback	Intervention period	Total intervention duration	Subtype of attentional performance
Nouchi et al., (2021)	Healthy adults	Not reported	NIRS	Increase bilateral dorsolateral prefrontal cortex activity	Block-puzzle game	Visual	4 weeks	20 min × 28 sessions	S + E
Shokri and Nosratabadi, (2021)	Novice male basketball players	Not reported	EEG	Increase SMR power (13–15 Hz) and alpha power (8–12 Hz); Decrease theta power (4–8 Hz) and beta3 power (18–35 Hz) (Cz, Cpz)	Biofeedback	Unclear	8 weeks	20 min × 24 sessions	E
Xia et al., (2021)	Healthy adults	Not reported	NIRS	Increase prefrontal (Ch. 1–22), parietal (Ch. 23–40), and temporal (Ch. 41,42) lobe activities	No intervention	Visual	3 days	more than 30 min × 3 sessions	A + E
Brandmeyer and Delorme, (2020)	Healthy adults	Not reported	EEG	Increase frontal-midline theta power (4–6 Hz; Fpz, Fz, F7, F8, Cz, P7, P8, Oz)	sham-NFT	Visual	2 weeks	30 min × 8 sessions	A + E
Christie et al., (2020)	Ice hockey players	Not reported	EEG	Increase SMR power (12–15 Hz); Decrease theta power (4–7 Hz) and high beta power (23–35 Hz) (Cz)	No intervention	Audio-Visual	4.5 months	75 min × 15 sessions	E

Study	Participant demographics	Adverse effects	Neuroimaging modality	Intervention(s) and EEG recording sites	Type of control condition	Type of feedback	Intervention period	Total intervention duration	Subtype of attentional performance
Gordon et al., (2020)	Healthy adults	Not reported	EEG	Increase alpha power (8–12 Hz; Pz)	Working memory training / Visual search training task / No intervention	Visual	5 weeks	20–50 min × 10 sessions	E
Maszczyk et al., (2020)	Judo athletes	Not reported	EEG	Increase beta1 power (13–20 Hz); Decrease theta power (4–7.5 Hz) and beta2 power (20–30 Hz) (Cz)	sham-NFT	Audio-Visual	6 weeks	(first half) 10 min × 15 sessions → (second half) 4 min × 15 sessions	E
Morgenroth et al., (2020)	Females with high anxiety	Not reported	fMRI	Increase functional connectivity between anterior cingulate cortex and left dorsolateral prefrontal cortex	sham-NFT	Visual	around 1 week	14 min × 2 sessions	E
Wang et al., (2020)	Healthy adults	Not reported	fMRI	Increase left or right intra-parietal sulcus activity	Unclear	Visual	3 weeks	90–120 min × 3 sessions	S
Balconi et al., (2019)	Healthy adults with a driver's license	Not reported	EEG	Unclear	No intervention	Visual	3 weeks	10–20 min × 21 sessions	S + A + E
Crivelli et al., (2019a)	Athletes and healthy adults	Not reported	EEG	Increase and decrease N2 power (forehead)	No intervention	Audio	2 weeks	10–20 min × 14 sessions	S + E

Study	Participant demographics	Adverse effects	Neuroimaging modality	Intervention(s) and EEG recording sites	Type of control condition	Type of feedback	Intervention period	Total intervention duration	Subtype of attentional performance
Crivelli et al., (2019b)	Healthy adults with mild stress	Not reported	EEG	Increase or decrease beta power (12–30 Hz) and decrease alpha power (8–12 Hz) (Fz, Cz, Pz)	No intervention	Visual	4 weeks	10–20 min × 28 sessions	S + E
Kim et al., (2019)	Healthy adults	Not reported	fMRI	Increase default-mode, salience, and executive network activities	sham-NFT	Visual	Unclear	300–390 s × 2 sessions	A
Sherwood et al., (2019)	Healthy adults	Not reported	fMRI	Decrease auditory cortex activity	sham-NFT	Audio	3 weeks	8 sessions (duration per day is unclear)	A
Arvaneh et al., (2018)	Healthy adults	Not reported	EEG	Increase P300 power (Fz, C3, Cz, C4, P3, Pz, P4, Oz)	No intervention	Visual	1 day	less than 1 h (including preparation) × 1 session	S + A
Gonçalves et al., (2018)	Healthy adults	Not reported	EEG	Increase SMR power (13–15 Hz); Decrease theta power (4–8 Hz) (Cz)	NFT in the reverse direction	Visual	1 day	1 session (duration per day is unclear)	S + A + E
Mikicin et al., (2018)	Professional soldiers	Not reported	EEG	Increase beta power (12–22 Hz; F3, F4, P3, P4)	sham-NFT	Unclear	Unclear	40 min × 20 sessions	A

Study	Participant demographics	Adverse effects	Neuroimaging modality	Intervention(s) and EEG recording sites	Type of control condition	Type of feedback	Intervention period	Total intervention duration	Subtype of attentional performance
Chow et al., (2017)	Healthy adults	None	EEG	Increase alpha power (8–12 Hz; Pz)	mindfulness meditation / sham-NFT	Audio	Unclear	18 min (number of sessions is unclear)	A + E
Hudak et al., (2017)	Healthy adults with high impulsivity and subclinical characteristics of ADHD	Not reported	NIRS	Increase frontal lobe activity	EMG-based biofeedback	Visual	2 weeks	8 sessions (duration per day is unclear)	E
Bhayee et al., (2016)	Healthy adults	Not reported	EEG	Unclear (two electrodes on the forehead)	No intervention	Audio	6 weeks	42 sessions (duration per day is unclear)	E
Gadea et al., (2016)	Healthy adult females	Not reported	EEG	Increase SMR power (12–15 Hz; Cz)	sham-NFT	Audio	Unclear	45 min (number of sessions is unclear)	S
Hsueh et al., (2016)	Healthy adults	None	EEG	Increase alpha power (8–12 Hz; C3a, C3p, Cza, Czp, C4a, C4p)	sham-NFT	Visual	4 weeks	36 min × 12 sessions	E
Cheng et al., (2015)	Golfers	Not reported	EEG	Increase SMR power (12–15 Hz; Cz)	sham-NFT	Audio	5 weeks	30–45 min × 8 sessions	E

Study	Participant demographics	Adverse effects	Neuroimaging modality	Intervention(s) and EEG recording sites	Type of control condition	Type of feedback	Intervention period	Total intervention duration	Subtype of attentional performance
Kober et al., (2015)	Healthy adults	Not reported	EEG	Increase SMR power (12–15 Hz; Cz, FPz)	sham-NFT	Visual	3–4 weeks	40 min × 10 sessions	E
Okazaki et al., (2015)	Healthy adults	Not reported	MEG	Increase alpha power (8–12 Hz)	sham-NFT	Visual	Unclear	Unclear	S
Enriquez-Geppert et al., (2014)	Healthy adults	Not reported	EEG	Increase frontal-midline theta power (Individualized Peak; Fz, FC1, FC2, FCz, Cz)	sham-NFT	Visual	2 weeks	30 min × 8 sessions	E
Gevensleben et al., (2014)	Healthy adults	Not reported	EEG	Increase and decrease SCP (Cz)	sham-NFT	Visual	3 weeks	90 min × 8 sessions	A
Salari et al., (2014)	Healthy adults	Not reported	EEG	Increase gamma power (40 Hz; PO7, PO8)	sham-NFT	Visual	3 days	2 h 16 min × 3 sessions	S
Studer et al., (2014)	Healthy adults	Not reported	EEG	Decrease theta power (4–7 Hz) and beta power (22–36 Hz)	NFT (increase and decrease SCP)	Visual	5 weeks	50 min × 10 sessions	S + A + E

Study	Participant demographics	Adverse effects	Neuroimaging modality	Intervention(s) and EEG recording sites	Type of control condition	Type of feedback	Intervention period	Total intervention duration	Subtype of attentional performance
Ghaziri et al., (2013)	Healthy adults	Not reported	EEG	Increase beta1 power (15–18 Hz; F4, P4)	sham-NFT / No intervention	Visual	13.5 weeks	30 min × 40 sessions	A
Wang et al., (2013)	High anxiety	Not reported	EEG	Increase alpha power (8–13 Hz); Decrease delta power (1–4 Hz) (C3 or C4)	sham-NFT	Audio	7.5 weeks	27 min × 15 sessions	E
Logemann et al., (2010)	Healthy adults with high impulsivity or high inattention	Not reported	EEG	Increase SMR power (Cz, Pz, C3, P3, C4)	sham-NFT	Unclear	8 weeks	22 min × 16 sessions	A + E
Fritson et al., (2008)	Healthy adults	Not reported	EEG	Increase SMR power (12–15 Hz); Decrease theta power (4–7 Hz) and beta power (22–36 Hz) (C3, C4)	sham-NFT	Audio-Visual	Unclear	Unclear	A + E
Egner and Gruzelier, (2004a)	Healthy adults	Not reported	EEG	① Increase beta1 power (15–18 Hz); Decrease theta power (4–7 Hz) and high beta power (22–30 Hz) (Cz) ② Increase SMR power (12–15 Hz); Decrease theta power (4–7 Hz) and high beta power (22–30 Hz) (Cz)	Alexander Technique	Audio-Visual	10 weeks	15 min × 10 sessions	S + A

Study	Participant demographics	Adverse effects	Neuroimaging modality	Intervention(s) and EEG recording sites	Type of control condition	Type of feedback	Intervention period	Total intervention duration	Subtype of attentional performance
Vernon et al., (2003)	Healthy adults	Not reported	EEG	Increase SMR power (12–15 Hz); Decrease theta power (4–8 Hz) and beta power (18–22 Hz) (Cz)	No intervention / NFT (increase theta power)	Audio-Visual	4 weeks	15 min × 8 sessions	A + E
Mikulka et al., (2002)	Healthy adults	Not reported	EEG	Increase beta power (13–30 Hz); Decrease theta power (4–7 Hz) and alpha power (8–12 Hz) (F3, F4, O1, O2)	sham-NFT / NFT (decrease engagement index)	Unclear	1 day	40 min × 1 session	A
Hord et al., (1976)	Sleep deprivation (40 h)	Not reported	EEG	Increase alpha power (10 Hz; O2)	NFT (decrease alpha and theta powers (4-14 Hz))	Audio	2 days	60 min × 2 sessions	A

Abbreviations: NIRS, Near infra-red spectroscopy; EEG, Electroencephalogram; fMRI, Functional magnetic resonance imaging; MEG, Magnetoencephalography; NFT, Neurofeedback training; Ch., Channel; EMG, Electromyography; SMR, Sensorimotor rhythm; SCP, Slow cortical potential; E, Executive function; S, Spatial orienting; A, Arousal