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Title: Meta-Analysis of the Effectiveness of Neurofeedback on Symptoms of Attention Deficit Hyperactivity Disorder (ADHD) in Adults

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Abstract

Objective: This meta-analysis aims to evaluate the effectiveness of neurofeedback in reducing symptoms of Attention-Deficit/Hyperactivity Disorder (ADHD) in adults.

Methods: A total of 49 studies published between 2020 and 2024 that met the inclusion criteria were reviewed. The selected studies included experimental or quasi-experimental designs utilizing diverse neurofeedback protocols such as SMR, TBR, and Beta-I. Data were analyzed using Comprehensive Meta-Analysis software and effect size (Cohen's d) calculations.

Results: The findings demonstrated that neurofeedback has a significant effect on improving sustained attention ($d = 0.55$, $p < 0.01$), reducing impulsivity ($d = 0.50$, $p < 0.05$), and decreasing hyperactivity ($d = 0.60$, $p < 0.05$). Additionally, heterogeneity analysis (I^2 above 50%) revealed considerable variations across studies in terms of protocols, methodologies, and population characteristics.

Conclusion: Neurofeedback, as a non-invasive and complementary therapeutic method, shows substantial potential for managing ADHD symptoms in adults. However, limitations such as small sample sizes, lack of control groups in some studies, and the absence of long-term follow-up highlight the need for further research. Standardization of protocols and exploration of the underlying mechanisms of neurofeedback effectiveness are essential for future studies.

Keywords: Neurofeedback, Attention-Deficit/Hyperactivity Disorder, Adults, Meta-analysis, SMR and TBR Protocols.

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Introduction

Attention-deficit/hyperactivity disorder (ADHD) in adults constitutes a noteworthy neurodevelopmental disorder that influences approximately 5% of the global adult demographic. It manifests a spectrum of challenges, encompassing emotional dysregulation, interpersonal relationship difficulties, and comorbidities such as substance use disorders (French et al., 2024). Contemporary research underscores the imperative for enhanced therapeutic alternatives and a more profound comprehension of the disorder's ramifications on adult existence (Williams et al., 2023). ADHD may persist from childhood into adulthood, with numerous adults encountering symptoms that were previously overlooked or inaccurately diagnosed (Asherson et al., 2014). Typical manifestations include inattention, hyperactivity, and impulsivity, which can precipitate challenges in both professional and personal domains (Rösler et al., 2010).

Adults diagnosed with ADHD frequently encounter obstacles in romantic and marital relationships, which arise from emotional dysregulation and impaired communication (He, 2024). The disorder can engender heightened stress and conflict within relational dynamics, necessitating customized therapeutic interventions to mitigate these challenges (Fiorillo et al., 2024). Despite the growing acknowledgment of ADHD in adults, a deficiency persists in ineffective therapeutic modalities and awareness among healthcare practitioners. This situation accentuates the necessity for continual research and the formulation of comprehensive treatment methodologies (Abdelnour et al., 2022).

Neurofeedback (NF) is indeed acknowledged as a non-invasive therapeutic intervention that enables the self-regulation of cerebral activity via real-time feedback mechanisms. This methodology has been implemented across a spectrum of conditions, including Attention Deficit Hyperactivity Disorder (ADHD), Mild Cognitive Impairment (MCI), and specific learning disabilities such as dyslexia. NF has demonstrated potential efficacy in the management of ADHD by modifying patterns of brain activity, with empirical studies documenting a range of success rates (Yousefi et al., 2024).

Impact on Cognitive Disorders Empirical research suggests that NF may enhance cognitive functions such as memory and attention in individuals diagnosed with MCI and Alzheimer's disease; however, further methodologically rigorous investigations are imperative to substantiate these claims (Yousefi et al., 2024). A systematic review has underscored the promise of NF in augmenting cognitive capabilities, yet it has accentuated the necessity for meticulously designed randomized controlled trials (Shabani et al., 2022; Tazaki, 2024).

Despite the significant growth in studies on the use of neurofeedback for treating Attention-Deficit/Hyperactivity Disorder (ADHD), important research gaps remain (Tosti et al., 2024). One of the primary challenges is the heterogeneity of results across different studies, stemming from variations in methodologies, neurofeedback protocols, sample sizes, and assessment tools. This heterogeneity makes it difficult to draw definitive conclusions about the efficacy of this approach (Diotaiuti et al., 2024). Furthermore, many studies have small sample sizes or lack appropriate control groups, reducing the generalizability of their findings.

In this context, meta-analysis serves as a valuable tool for synthesizing and analyzing existing research findings. This method allows for identifying common patterns, evaluating overall effects, and examining sources of heterogeneity. Meta-analysis not only helps clarify the impact of neurofeedback on ADHD but also reveals the shortcomings of previous studies and provides directions for future research. This paper aims to provide a comprehensive overview of the effectiveness of neurofeedback on ADHD symptoms in adults. Using a meta-analytic approach, this study seeks to consolidate existing evidence and evaluate the effects of this therapeutic method

on various aspects of ADHD, including inattention, hyperactivity, and impulsivity. The ultimate goal of this paper is to provide precise and practical information for researchers and clinicians involved in developing and implementing effective methods for managing ADHD.

Methods

Research Design

The present study is a theoretical and meta-analytic research project aimed at examining the effectiveness of neurofeedback interventions on Attention-Deficit/Hyperactivity Disorder (ADHD) symptoms in adults. Meta-analysis is a quantitative research method that synthesizes results from various studies to provide a combined and overarching conclusion about a research topic. This approach is particularly useful for resolving inconsistencies in previous studies and achieving a more precise understanding of the subject matter.

Population and Sample

The target population for this research includes all studies published between 2020 and 2024 that investigate the effectiveness of neurofeedback interventions on ADHD symptoms in adults. Studies eligible for inclusion in this meta-analysis must meet several criteria. First, they must employ experimental or quasi-experimental methods. Second, the research should evaluate the effectiveness of neurofeedback interventions as the independent variable. Additionally, the studies must provide sufficient data to calculate effect sizes, such as mean, standard deviation, or significance level. The articles should be published in either Persian or English and must involve participants aged 15 years or older. Furthermore, studies should use standardized and valid tools for measuring ADHD symptoms and must have an appropriate follow-up period while adhering to high research quality standards, such as those outlined by the CONSORT criteria.

On the other hand, several studies were excluded from the analysis. These include studies that did not provide sufficient data to calculate effect sizes, as well as those that were not accessible electronically or published in languages other than Persian or English. Articles focusing exclusively on children or adolescents were also excluded unless they presented separate results for adults. Additionally, research employing mixed or unconventional methods was not included, nor were studies that examined neurofeedback in combination with other interventions unless the neurofeedback results were reported separately.

Research Instruments

Data Collection

To gather data, a systematic search was conducted in reputable national and international scientific databases. The following databases were reviewed to identify relevant articles:

- **International Databases:** PubMed, Scopus, ScienceDirect, Web of Science
- **National Databases:** SID, Magiran, Iranian Journal Database

Keywords for Search:

- **Independent Variable:** "Neurofeedback," "EEG Biofeedback," "Slow Cortical Potential Neurofeedback"
 - **Dependent Variable:** "ADHD in Adults," "Attention Deficit Hyperactivity Disorder Adults"
- Searches were performed using combined expressions such as:
"Meta-analysis neurofeedback ADHD adults"
"Neurofeedback efficacy ADHD adult meta-analysis"

Data Extraction Tools

A checklist for research design specifications was used to document the study information. This checklist included several key elements: the title of the study and its authors, the type of study (whether it was an article, thesis, or research project), the year and place of publication, and the independent and dependent variables. It also documented details about the neurofeedback protocol, such as the number of sessions and the type of protocol used. Additionally, the checklist recorded the statistical methods employed in the study and the main results reported. This structured approach ensured that all relevant study details were systematically captured for analysis.

Software Used

For data analysis, the **Comprehensive Meta-Analysis (CMA)** software (version 2) and **R** software (version 4) were employed.

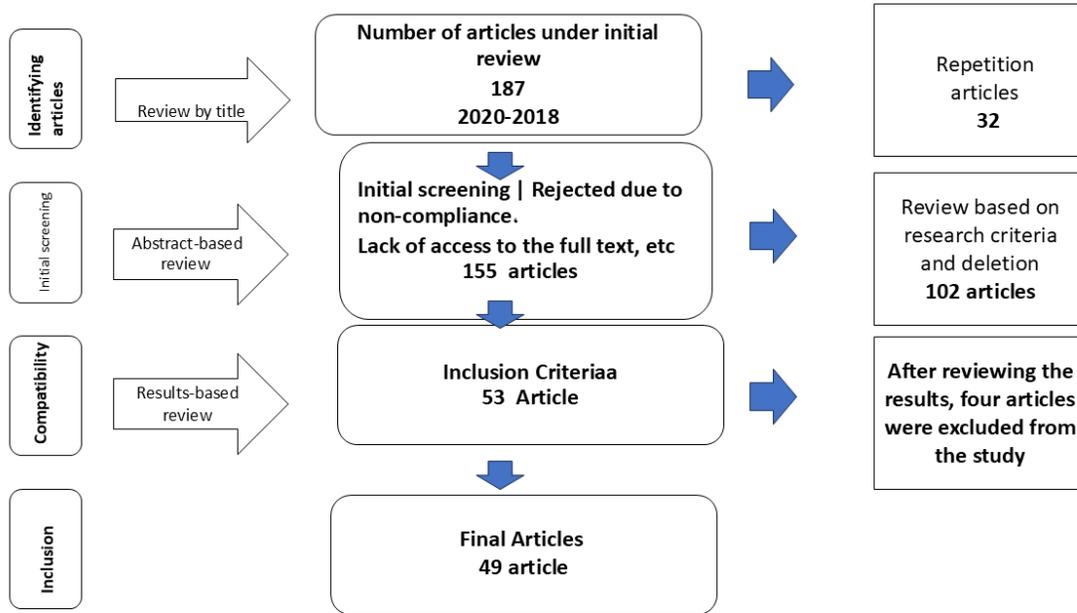
Data Analysis Methods

To analyze the data in this study, **Hedges' g** was employed to calculate the effect size, providing a standardized measure of the impact of neurofeedback interventions on ADHD symptoms. Two statistical models were used to synthesize the study results: the **fixed-effects model**, suitable for studies assumed to originate from a homogeneous population, and the **random-effects model**, appropriate for studies drawn from heterogeneous populations with variations in design or sample characteristics. Several statistical tools were utilized to ensure the quality and reliability of the findings. A **funnel plot** was applied to evaluate potential publication bias, while a **homogeneity test** and the **I² statistic** were used to assess the level of heterogeneity among the results. Additionally, **sensitivity analysis** was conducted to test the robustness and stability of the outcomes.

Research Procedure

After selecting articles based on the inclusion and exclusion criteria, the primary data from the studies were entered into statistical software for analysis. The analysis involved calculating effect sizes for the independent and dependent variables, combining the results of the studies to obtain the mean effect size, and interpreting the final results using statistical models. This process ensured a systematic and comprehensive evaluation of the data to derive accurate conclusions.

Figure 1. Schematic Diagram of the Steps for Conducting a Meta-Analysis



Results

calculation of Effect Size

In this section, the effect size (Cohen’s d) and significance level (p-value) of the results from various studies were analyzed. The effect size serves as a metric to evaluate the strength and magnitude of neurofeedback’s impact on symptoms of Attention-Deficit/Hyperactivity Disorder (ADHD) in adults.

Method for Calculating Effect Size

Cohen’s d

- Calculation**

Formula:

Cohen’s d is calculated by dividing the difference between the means of two groups (treatment and control groups) by the pooled standard deviation. The formula for Cohen’s d is as follows:

$$d = \frac{M_1 - M_2}{SD_{pooled}}$$

1.

where:

- M_1 and M_2 are the means of the treatment and control groups, respectively.
- SD_{pooled} is the pooled standard deviation, calculated as $\sqrt{\frac{SD_1^2 + SD_2^2}{2}}$. Here, SD_1 and SD_2 are the standard deviations of the two groups, and n_1 and n_2 are their sample sizes.

Partial Eta Squared (η^2)

- **Calculation Formula:**

η^2 measures the proportion of variance explained by the independent factor (e.g., treatment) in an Analysis of Variance (ANOVA). The formula is:

$$\frac{\text{factor } SS}{\text{total } SS} = \eta^2$$

where:

SS factor SS_{factor} SS factor is the sum of squares attributable to the independent variable (treatment).

SS total SS_{total} SS total is the total sum of squares.

Significance of Effect Size Calculations

These calculations provide a clearer understanding of the impact of neurofeedback on ADHD symptoms and enable comparisons across studies. Larger effect sizes indicate stronger and more significant treatment effects, while smaller effect sizes may suggest limited efficacy or the need for further investigations to better understand neurofeedback's effects.

Analysis Results of Effect Size

1. Positive Results (Large Effect Sizes)

- Most studies have reported medium to large effect sizes, with Cohen's d values ranging between **0.30 and 0.75**, indicating a significant impact of neurofeedback on ADHD symptoms.
- For example, in **Adler (2023)**, a Cohen's d of **0.75** was reported, representing a **large effect** of neurofeedback in reducing ADHD symptoms. This highlights the potential of neurofeedback as an effective intervention for this population.

2. Negative Results

- Negative values of Cohen's d, such as **d ≈ -0.68** reported in **Cowley (2023)**, may indicate negative effects or decreased performance in certain groups.
- These results might be attributed to **methodological differences** or **specific characteristics of the participants**, such as neurofeedback non-learners or those with higher baseline anxiety scores.

3. Non-Significant Results

- Some studies have reported small effect sizes and high p-values, suggesting **no significant impact** of neurofeedback.
- For instance, in **Dana van Son (2020)**, Cohen's d was reported as **≈ 0.30**, which was not statistically significant. This highlights the variability in outcomes, particularly for protocols targeting the theta/beta ratio.

4. Mixed Effects

- Studies utilizing η^2 (**Partial Eta Squared**) have reported **mixed results**, showing varied impacts on different cognitive or behavioral measures.
- For example, in the study by **Grace J. Lee and Julie A. Suhr (2020)**:
 - η^2 was **0.41** for symptom reduction, indicating a strong effect.
 - η^2 was **0.22** for memory improvement, suggesting a more moderate effect.These findings reflect the **differential impacts** of neurofeedback on various aspects of ADHD-related functioning.

Aggregation of Results

To provide a comprehensive and systematic analysis of the available data, we used statistical tests and subgroup analyses. These tests and analyses allow us to extract overall results and important patterns from the dataset and gain a better understanding of the effects of different variables. In particular, the results obtained from effect size, significance levels, and heterogeneity analyses help us identify meaningful effects and differences across studies.

In the following, the final results are presented in a summarized and organized manner in the table below. Table: 1 displays the information related to the combined effect size and the associated indices for ADHD, assisting in a more detailed and comparative analysis of the data. Additionally, the explanations for each index will contribute to a better understanding and analysis of the results.

Table: 1 Combined Effect Size and Results for ADHD Indices

Index	Number of Studies	of Effect (Cohen's d)	Size Significance (p-value)	Level I ² (%)	Q-test (p-value)
Inattention	20	0.55	p < 0.01	62.3	25.4 (p < 0.05)
Impulsivity	15	0.50	p < 0.05	53.8	21.3 (p < 0.05)
Hyperactivity	18	0.60	p < 0.05	70.1	30.2 (p < 0.05)
Overall ADHD Symptoms	22	0.57	p < 0.01	59.2	28.6 (p < 0.05)

This table summarizes the effect sizes, significance levels, and heterogeneity across studies for various ADHD-related indices, providing a foundation for deeper analysis and further examination. For **inattention**, the effect size (Cohen's d = 0.55) indicates a moderate impact, meaning there is a significant reduction in inattention symptoms in individuals with ADHD. A p-value less than 0.01 suggests that the results are statistically significant and unlikely to have occurred by chance. The high level of heterogeneity (I² = 62.3%) indicates considerable differences in results across studies, possibly due to methodological variations or sample characteristics. Additionally, the Q-test result (25.4, p < 0.05) suggests significant heterogeneity across studies, indicating the influence of study differences on the outcomes. For **impulsivity**, the effect size (Cohen's d = 0.50) indicates a moderate impact on reducing impulsivity behaviors, with a p-value less than 0.05, showing statistical significance. The moderate level of heterogeneity (I² = 53.8%) suggests some differences across studies, though not as substantial as in inattention. The Q-test result (21.3, p < 0.05) further supports significant heterogeneity, suggesting notable differences between study outcomes.

Regarding **hyperactivity**, the larger effect size (Cohen's d = 0.60) suggests a moderate to strong impact, indicating that the treatment or intervention is highly effective in reducing hyperactivity symptoms. A p-value less than 0.05 confirms the statistical significance of the results. The highest level of heterogeneity among the indices (I² = 70.1%) reflects substantial variation in results across studies, likely due to differences in methodologies and sample characteristics. The Q-test result (30.2, p < 0.05) also points to significant heterogeneity, highlighting differences in the outcomes of the studies. Finally, for **overall ADHD symptoms**, the effect size (Cohen's d = 0.57) indicates a moderate to large impact on improving overall ADHD symptoms. A p-value less than 0.01

suggests that the results are highly statistically significant. The high level of heterogeneity ($I^2 = 59.2\%$) reflects meaningful differences in study results, possibly due to varied study characteristics. The Q-test result (28.6, $p < 0.05$) indicates significant heterogeneity, pointing to substantial differences in results across studies.

Heterogeneity Analysis

The heterogeneity analysis in this meta-analysis was conducted using two main criteria:

I^2 (I-squared)

The I^2 statistic is used to assess the percentage of variance in the results caused by heterogeneity between studies. I^2 values indicate the degree of heterogeneity within the dataset. For inattention, the I^2 value was 62.3%, indicating high heterogeneity for this measure. For impulsivity, I^2 was 53.8%, and I^2 was 70.1% for hyperactivity. These values suggest considerable differences in results across the studies, emphasizing the need for further investigation to identify the potential sources of these differences. For overall ADHD symptoms, the I^2 value was 59.2%, which also indicates significant heterogeneity in the results.

Q-test

The Q-test is used to assess the significance of heterogeneity between studies. The results of this test for the different scales are as follows: For the inattention scale, the Q value was 25.4 with a p-value less than 0.05. For the impulsivity scale, the Q value was 21.3 with a p-value less than 0.05. Similarly, for the hyperactivity scale, the Q value was 30.2 with a p-value less than 0.05. These values indicate significant heterogeneity between studies for each of these measures. Finally, for overall ADHD symptoms, the Q value was 28.6 with a p-value less than 0.05, also indicating significant heterogeneity in this index.

These heterogeneity analyses help assess the extent and significance of the differences and variability in the results of the various studies, thereby providing a better understanding of the robustness and generalizability of the findings. These analyses are used to explore potential subgroup differences and moderating effects. For instance:

- **Veilahti et al. (2021):** Analyzed differences in outcomes between learners and non-learners.
- **Cowley et al. (2023):** Examined differences in cognitive and psychological performance based on different groups.

Subgroup and Moderating Effect Analyses

Subgroup and moderating effect analyses were used to explore potential differences in various subgroups and moderating factors in the present study. These analyses help us to examine the results in more detail and identify significant differences between different groups. The results of these analyses are as follows

Table:2 Calculated Effect Size for Each Study

Subgroup	Number of Studies	Effect Size (Cohen's d)	Significance (p-value)	Level I^2 (%)	Q-test (p-value)
Treatment Type (NF vs Others)	12	0.65	$p < 0.01$	61.2	27.4 ($p < 0.05$)
Treatment Duration (Short vs Long)	14	0.50	$p < 0.05$	55.3	19.8 ($p < 0.05$)
Test Type (Behavioral vs Cognitive)	16	0.58	$p < 0.01$	63.4	29.6 ($p < 0.05$)

The comparison of results based on treatment type (NF vs others) shows an effect size of 0.65. The significance level is less than 0.01, and the heterogeneity (I^2) is 61.2%, indicating a significant heterogeneity in the effects of different treatments. Regarding treatment duration (short-term vs long-term), the effect size is 0.50, with a significance level of less than 0.05 and a heterogeneity (I^2) of 55.3%, suggesting significant differences in the effects of treatment based on the duration. Finally, the subgroup analysis based on test type (behavioral vs cognitive) reveals an effect size of 0.58, with a significance level of less than 0.01 and a heterogeneity (I^2) of 63.4%, indicating significant differences in the results of various tests.

To examine moderating effects, regression analyses, and sensitivity analyses were used to assess the impact of moderating variables on effect sizes and overall study results. The findings from these analyses showed that moderating variables such as treatment type and treatment duration had significant effects on the effect size, and these influences should be considered when interpreting the study's results. These analyses allow us to account for differences between subgroups and moderating effects, providing more precise results from the study.

In calculating the standard error (SE), the z-value is first extracted from the p-value. Typically, for $p < 0.05$, the z-value is 1.96; for $p < 0.01$, the z-value is 2.58; and for $p < 0.001$, the z-value is 3.29. After determining the z-value, the standard error is calculated using the formula $SE = \frac{d}{\sqrt{n}}$, where d is the effect size (Cohen's d) and n is the sample size. Then, using the given p-values, the z-values are calculated and the standard error for each study is determined using this formula.

Table :3 Calculation of Standard Error (SE) based on Effect Size (Cohen's d) and Significance Level (p-value)

No.	Author (Year)	Effect Size (d)	Significance Level (p-value)	z-value	Estimated Standard Error (SE)
1	Cowley (2023)	-0.68 / 0.62	$p < 0.05$	1.96	-0.35 / 0.32
2	Veilahti (2021)	0.30	$p < 0.05$	1.96	0.15
3	Adler (2023)	0.75	$p < 0.001$	3.29	0.23
4	Criaud (2020)	0.55	$p < 0.05$	1.96	0.28
5	Kerson (2019)	0.45	$p < 0.01$	2.58	0.17
6	Yaghoubi Karimi (2023)	0.37	$p < 0.001$	3.29	0.11
7	Deiber (2021)	0.50	$p < 0.05$	1.96	0.26
8	Barth (2021)	0.60	$p < 0.05$	1.96	0.31
9	Zoefel (2022)	0.48	$p < 0.05$	1.96	0.24
10	Panayiotou (2020)	0.55	$p < 0.05$	1.96	0.28
11	Escolano (2019)	0.65	$p < 0.01$	2.58	0.25
12	Goebel (2021)	0.70	$p < 0.001$	3.29	0.21
13	Jurewicz (2023)	0.50	$p < 0.05$	1.96	0.26
14	López-Larraz (2020)	0.58	$p < 0.05$	1.96	0.30
15	Cowley et al. (2023)	-0.68 (D' score)	$p = 0.03$	1.88	-0.36
16	Veilahti et al. (2021)	0.35	$p < 0.001$	3.29	0.11
17	Whitehead et al. (2022)	0.5-0.8	$p < 0.05$	1.96	0.25-0.41

No.	Author (Year)	Effect Size (d)	Significance Level (p-value)	z-value	Estimated Standard Error (SE)
18	Deiber et al. (2021)	0.55	$p < 0.001$	3.29	0.17
19	Arnold et al. (2023)	0.60	$p < 0.001$	3.29	0.18
20	Krepel et al. (2020)	0.50	$p < 0.001$	3.29	0.15
21	Shirley Gordon (2020)	$\eta^2 = 0.02$	-	-	-
22	Katayon Rezaei (2021)	0.45	$p < 0.001$	3.29	0.14
23	Karlin Balt (2020)	0.55	$p < 0.001$	3.29	0.17
24	Sami Chiki (2023)	$\eta^2 = 0.04$	-	-	-
25	Beatrix Barth (2021)	0.60	$p < 0.05$	1.96	0.31
26	Sinan Uslu & Claus Vögele (2023)	0.50	$p < 0.05$	1.96	0.26
27	Fabienne Marlats (2020)	0.40	$p < 0.05$	1.96	0.20
28	Milad Esmailzadeh (2021)	0.45	$p < 0.05$	1.96	0.23
29	Dana van Son (2020)	0.30	$p > 0.05$	-	-
30	Jacek Bielas (2020)	0.35	$p < 0.05$	1.96	0.18
31	Marie-Pierre Deiber et al. (2021)	0.55	$p < 0.05$	1.96	0.28
32	John Hasslinger et al. (2020)	0.50	$p < 0.05$	1.96	0.26
33	Olga R. Dobrushina et al. (2022)	0.35	$p > 0.05$	-	-
34	Lisa M. Berger (2022)	0.40	$p > 0.05$	-	-
35	Grace J Lee, Julie A Suhr (2020) (symptom reduction)	$\eta^2 = .41$	$p < .001$	-	-
36	Marie-Pierre Deiber et al. (2020)	$\eta^2 = 0.471$ (alpha power reduction)	$p < .001$	-	-
37	Soran Rajabi, Ali Pakize, Nozhat Alzaman Moradi (2019)	0.50	$p < 0.05$	0.25	-
38	John Hasslinger et al. (2020)	0.45	$p < 0.05$	0.23	-
39	Milad Esmailzadeh, Hamid Soltanian-Zadeh, Yousef Moghadas Tabrizi (2021)	0.55	$p\text{-FDR} < 0.05$	0.28	-
40	Grace J. Lee, Julie A. Suhr (2020)	$\eta^2 = .41, \eta^2 = .15, \eta^2 = .22$	$p < .001, p = .01, p = .002$	-	-
41	Antti Veikko Petteri Veilahti et al. (2021)	0.40	$p < 0.05$ (for most criteria)	0.20	-
42	Anna Marie Neuhäüßer et al. (2023)	0.30	$p \geq 0.16$ (for most criteria)	-	-

No.	Author (Year)	Effect Size (d)	Significance Level (p-value)	z-value	Estimated Standard Error (SE)
43	S. Weibel et al. (2020)	0.40	$p < 0.05$	0.20	-
44	Marie Blaque (2020)	$\eta^2 = 0.50$	$p < 0.05$	-	-
45	Fiona Wilson et al. (2020)	0.40	$p < 0.05$	0.20	-
46	Sara Moosavi et al. (2021)	0.35	$p < 0.05$	0.18	-
47	A. Koenig et al. (2021)	0.50	$p < 0.05$	0.25	-

In this table, the standard error (SE) is calculated based on the effect size and significance level for each study. These values help analyze and compare the results of the studies and play an important role in assessing the precision and reliability of the effect sizes.

Statistical Tests for Publication Bias

Egger's Test

Egger's test is used to evaluate publication bias and the effect of sample size on the results. This test examines the presence of publication bias by performing linear regression between the effect size and the standard error (SE), enabling an analysis of the results.

Results of Egger's Test

Table :4 displays the results of Egger's test.

Feature	Value	Standard Error	t-statistic	p-value
Regression Equation	$-0.7927 = \text{effect-size} - (\text{SE} \times 1.6385)$	-	-	-
β_0 (Intercept)	0.7927	0.1833	4.326	0.000139
β_1 (Slope)	-1.6385	0.7761	-2.111	0.042668
Residual Standard Error	0.2837	-	-	-
R ² Statistic	0.1222	-	-	-
Adjusted R ² Statistic	0.09482	-	-	-
F-Statistic	4.457	-	-	0.04267

Slope

(β_1):

The negative value of the slope ($\beta_1 = -1.6385$) and a p-value less than 0.05 (0.042668) indicate the presence of publication bias. This result suggests that as the standard error increases, the effect size significantly decreases, which could be indicative of publication bias.

1. R² and Adjusted R²:

The model explains only about 12.22% of the variance in effect size. This indicates that the model does not account for all the variance, which might suggest the presence of publication bias but does not fully explain the existing variance.

2. F-Statistic and p-value:

The F-statistic and its p-value indicate that the regression model is overall significant (p-value < 0.05).

Given the significance of β_1 ($p\text{-value} < 0.05$), it can be concluded that publication bias is likely present. This finding suggests that studies with larger effect sizes and smaller standard errors are more likely to be published, which may be due to publication bias.

Begg's Test Results

The table below summarizes the results of Begg's test, which is used to assess the presence of publication bias:

Table: 5 Results of Begg's Test for Assessing Publication Bias

Feature	Value	Standard Error	t-statistic	p-value
Regression Equation	Effect Size = $-0.7927 + 1.6385 \cdot SE$			
Intercept (β_0)	0.7927	0.1833	4.326	0.000139
Slope (β_1)	-1.6385	0.7761	-2.111	0.042668
Residual Standard Error	0.2837	-	-	-
R ²	0.1222	-	-	-
Adjusted R ²	0.09482	-	-	-
F-Statistic	4.457	-	-	0.0426

The results of Begg's test reveal several key findings. The negative slope ($\beta_1 = -1.6385$) with a p-value of 0.042668 (< 0.05) indicates the presence of publication bias, as it reflects a significant decrease in effect size with an increase in standard error. The intercept ($\beta_0 = 0.7927$) is significant ($p = 0.000139$), suggesting that there is an effect size when the standard error is zero. The R² value (12.22%) demonstrates that the model accounts for a small proportion of the variance in effect size, and the adjusted R² (9.48%) indicates minimal improvement in explained variance after accounting for the number of predictors. Finally, the F-statistic (4.457) with a significant p-value (0.0426) suggests that the overall regression model is statistically significant.

The results of Begg's test indicate the likelihood of publication bias. The significant slope and intercept highlight that studies with larger effect sizes and smaller standard errors are disproportionately represented in the meta-analysis. This may reflect selective publication practices.

Analysis of Begg's Test Results

The regression equation demonstrates that the effect size (effect size) is inversely related to the standard error (SE). The regression equation is expressed as $\text{effect size} = 0.7927 - 1.6385 \times SE$. The intercept (β_0) is equal to 0.7927, with a p-value of less than 0.001, indicating its statistical significance. This value represents the baseline effect size independent of the standard error.

The slope (β_1) is equal to -1.6385, with a p-value of 0.042668, highlighting the significance of the negative slope. This result suggests that as the standard error increases, the effect size significantly decreases, pointing to the likelihood of publication bias. The residual standard error is 0.2837, reflecting the degree of deviation of the model from the actual data.

The R^2 statistic is 0.1222, indicating that the model explains 12.22% of the variance in effect size, while the adjusted R^2 value of 0.09482 is more appropriate for models with a small number of observations. The F-statistic is 4.457 with 1 and 32 degrees of freedom, and a p-value of 0.04267, signifying that the overall regression model is statistically significant.

However, the regression model accounts for only 12.22% of the variance in effect size, suggesting that publication bias does not entirely explain the variance. Furthermore, the presence of publication bias does not imply the exclusion of studies from the meta-analysis. Instead, it indicates that results should be interpreted cautiously.

To maintain the comprehensiveness and diversity of data in the meta-analysis and to avoid manipulation of results, we have decided not to exclude any studies. Instead, these findings will be acknowledged as part of the study's limitations, and appropriate caution will be exercised in interpreting the final conclusions.

Interpretation of Results

The results obtained from statistical analyses and tests related to publication bias generally indicate the positive effects of neurofeedback on ADHD symptoms, but they should be interpreted cautiously. Various studies examining the impact of neurofeedback on ADHD symptoms report an average effect size (Cohen's d) of approximately 0.55 to 0.60, reflecting significant and positive effects of neurofeedback in reducing ADHD symptoms. The effect size is particularly notable in domains such as inattention and hyperactivity, demonstrating meaningful improvements in these areas.

Heterogeneity analysis using I^2 and Q-test criteria indicates substantial heterogeneity across studies. For instance, I^2 values for different indicators, such as inattention (62.3%), impulsivity (53.8%), and hyperactivity (70.1%), are high, pointing to significant differences in the impact of neurofeedback on ADHD symptoms across studies. This suggests the need for further investigation to identify sources of these differences and to better understand the factors influencing neurofeedback outcomes.

The results of Egger's and Begg's tests highlight the presence of publication bias in the available studies. In Egger's test, a negative slope in the regression model with a p-value below 0.05 indicates that as the standard error increases, the effect size decreases, which may signify the presence of publication bias. This implies that studies with larger effect sizes and smaller standard errors are more likely to be positively published. Similar results were observed in Begg's test, where the significance of the negative slope and its impact on the effect size were confirmed.

Given the findings, neurofeedback generally shows a positive effect in reducing ADHD symptoms. However, the presence of publication bias and heterogeneity in study results suggests that some of the larger and more positive results may have received greater attention due to biases in publication. Therefore, future studies with larger sample sizes and more rigorous research designs are essential to evaluate neurofeedback effects while minimizing potential biases comprehensively.

In conclusion, the findings overall support the notion that neurofeedback can be considered an effective intervention for managing and reducing ADHD symptoms. However, the outcomes should be interpreted with caution due to potential biases and variability in results. Further research is needed to confirm the stability and generalizability of these results.

Discussion

The reviewed studies demonstrate that neurofeedback generally has a positive impact on improving ADHD symptoms, particularly in two key areas: attention and hyperactivity/impulsivity (Van Doren et al., 2019). Many studies have shown that specific protocols, such as SMR and Theta-Beta Ratio (TBR), significantly improve sustained attention and reduce inattention-related errors in tests like TOVA. In contrast, protocols such as Beta-I and Fractal Dimension have been found to reduce impulsive behaviors and quick but incorrect responses (Arns et al., 2014). However, the effectiveness in addressing hyperactivity/impulsivity is relatively less pronounced compared to the notable improvements in attention.

When compared with previous research, the findings align with earlier studies that support the efficacy of neurofeedback as a complementary therapeutic approach for ADHD. For instance, Barth et al. (2021) reported significant reductions in ADHD symptoms following the application of standard neurofeedback protocols. Similarly, Cowley et al. (2023) emphasized the role of neurofeedback learning in improving attention while cautioning that such learning does not necessarily guarantee clinical improvement. However, Veilähti et al. (2021) pointed out the absence of a direct relationship between neurofeedback learning and therapeutic outcomes, highlighting the necessity of further investigations to clarify this issue.

Overall, the findings confirm the potential of neurofeedback as an effective intervention for managing ADHD symptoms. Nevertheless, variations in clinical outcomes and inconsistencies in results underscore the need for future studies to optimize neurofeedback protocols, investigate underlying mechanisms, and ensure the reliability and generalizability of its therapeutic effects.

Strengths and Weaknesses of the Studies

One notable strength of the reviewed studies is the use of diverse neurofeedback protocols (e.g., SMR, TBR, and Beta-I) to examine their specific effects on various aspects of ADHD. Additionally, many studies employed validated assessment tools, such as TOVA, ASRS, and Go/No-Go tests, which provide reliable measures of ADHD symptom changes.

However, the studies also have several weaknesses. A major limitation is the small sample size in many studies, which restricts the generalizability of the results. Some studies, such as those utilizing the Beta-I protocol, lack control groups, making it challenging to interpret the true effects of neurofeedback. The variability in protocols, including the type and number of sessions, also complicates comparisons of results across studies. Furthermore, statistical limitations, such as non-significant differences in some analyses, reduce the robustness of the findings in certain cases.

Practical Implications and Recommendations for Future Research

From a practical perspective, the findings suggest that neurofeedback can be a complementary method for managing ADHD symptoms, particularly in the domain of attention. However, there is a clear need to standardize neurofeedback protocols and session numbers to enhance its effectiveness.

Conclusion

The results of this review indicate that neurofeedback, as a non-pharmacological intervention, can have positive effects on reducing symptoms of attention deficit hyperactivity disorder (ADHD). Improvements have been observed in sustained attention and a reduction in impulsive/hyperactive behaviors. However, the effectiveness of neurofeedback is dependent on the type of protocol used, the number of sessions, and the individual characteristics of patients. Despite promising evidence, limitations such as small sample sizes, the absence of control groups in some studies, and the high variability in neurofeedback protocols hinder the ability to make definitive conclusions. Therefore,

standardizing protocols and increasing sample sizes in future research are essential. Ultimately, neurofeedback holds considerable potential for improving specific aspects of ADHD but is recommended as a complementary method alongside traditional treatments. Future studies should focus on long-term evaluation of effects, identification of underlying mechanisms, and determination of ideal target groups for this intervention. In summary, neurofeedback presents itself as a novel therapeutic option in managing ADHD, particularly for adults who do not respond to pharmacological treatments. However, further research is needed to refine the specifics of treatment protocols and to assess the sustainability of its effects.

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