KMAN PUBLISHING INSTITUTE
Journal Website
Article history:
Received 17 March 2025
Revised 19 June 2025
Accepted 26 July 2025
Published online 01 August 2025

Psychological Research in Individuals with Exceptional Needs

Volume 3, Issue 3, pp 1-10

PRIEN
Psychological Research in Individuals with Exceptional Needs

E-ISSN: 3060-6713

The Effectiveness of Neurofeedback on Working Memory Performance and Cognitive Planning Ability in Children with Attention-Deficit/Hyperactivity Disorder

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A r t i c l e I n f o

Article type:
Original Research

How to cite this article:
Haghi Nomandan, S., & Haghi Nomandan, F. (2025). The Effectiveness of Neurofeedback on Working Memory Performance and Cognitive Planning Ability in Children with Attention-Deficit/Hyperactivity Disorder. *Psychological Research in Individuals with Exceptional Needs, 3*(3), 1-10.
https://doi.org/10.61838/kman.prien.3.3.9

A B S T R A C T

The present study aimed to examine the effectiveness of neurofeedback on working memory performance and cognitive planning ability in children with ADHD. This semi-experimental study employed a pretest–posttest control group design with a follow-up phase. The statistical population consisted of all children aged 7 to 14 years diagnosed with ADHD who attended the Shiva Counseling and Psychology Center in Rasht in 2025. From this population, 70 children (35 in the experimental group and 35 in the control group) were selected through purposive sampling. The experimental group received 20 sessions of neurofeedback training (two sessions per week, each lasting 30 to 40 minutes). The neurofeedback protocol involved reducing the theta/beta ratio in the F4 region, enhancing sensorimotor rhythm (SMR), and decreasing theta and delta activity in the frontal and Cz regions. Data collection instruments included the Conners-3 Questionnaire, the Wechsler Digit Span Subtest, the Corsi Block-Tapping Test for visuospatial memory, and the Tower of London Test for cognitive planning. Data were analyzed using descriptive statistics and mixed-design ANOVA with repeated measures in SPSS version 29. Results revealed that the mean scores of verbal and visuospatial working memory, cognitive planning ability, and the reduction of ADHD index significantly improved in the neurofeedback group compared to the control group in both posttest and follow-up stages ($p < .001$). The effects of time, group, and the interaction between time × group were significant across all variables (partial η^2 ranging from .43 to .70). Bonferroni post hoc tests indicated that the changes from pretest to posttest were significant and remained stable at the follow-up phase. Moreover, 76.5% of children in the neurofeedback group demonstrated a clinically significant reduction (more than 10 T-score points on the Conners Questionnaire). The findings suggest that neurofeedback, through the modulation of brainwave patterns in frontal and central regions, can produce lasting improvements in working memory and cognitive planning abilities among children with ADHD.

Keywords: *Attention-Deficit/Hyperactivity Disorder (ADHD); Cognitive Planning; Working Memory; Neurofeedback*

1. Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is a chronic neurodevelopmental disorder characterized by persistent patterns of inattention, hyperactivity, and impulsivity that interfere with functioning across multiple domains of life. It is one of the most prevalent disorders diagnosed during childhood, with global estimates suggesting that approximately 5–7% of school-aged children meet diagnostic criteria (Barkley, 2015). Beyond behavioral symptoms, ADHD has been associated with deficits in higher-order executive functions such as working memory, inhibitory control, and cognitive planning (Kofler et al., 2024). These deficits often persist into adolescence and adulthood, contributing to difficulties in academic achievement, emotional regulation, and social functioning (Louthrenoo et al., 2022).

Neurobiological investigations have revealed that ADHD involves dysregulation in cortical–subcortical circuits, particularly in the prefrontal cortex and fronto-striatal pathways, which are responsible for executive control, attention regulation, and inhibitory processes (Jounghani et al., 2024; Kofler et al., 2024). Functional imaging studies have demonstrated altered neural oscillations, particularly excessive theta activity and reduced beta power, which are believed to underlie attentional lapses and poor self-regulation (Wu et al., 2024; Zhang et al., 2024). Given these findings, interventions that aim to directly modulate cortical activity—such as neurofeedback training—have gained prominence as promising non-pharmacological treatments for ADHD (Himmelmeier & Werheid, 2024).

Traditional treatments for ADHD, such as stimulant medication and behavioral therapy, have shown substantial efficacy in symptom reduction; however, these approaches are not without limitations. Stimulant medications, while effective for many children, may cause adverse effects such as sleep disturbances, appetite suppression, and irritability, and may not sustain benefits over time (Sheikh et al., 2022). Behavioral interventions, on the other hand, require high levels of parental involvement and therapist supervision, limiting accessibility in resource-constrained settings (Shojaei, 2024). Consequently, researchers have increasingly turned to neurofeedback (NFB), a method rooted in the principles of operant conditioning, as a viable complementary or alternative therapy. NFB enables individuals to self-regulate neural oscillations by providing real-time feedback about their electroencephalographic (EEG) activity, reinforcing desirable brainwave patterns, and suppressing maladaptive ones (Hunkin et al., 2021; Viviani & Vallesi, 2021).

Empirical evidence supports the efficacy of neurofeedback in modulating attention and executive functioning. Systematic reviews and meta-analyses have shown that NFB can produce moderate-to-large effect sizes in reducing ADHD symptoms, particularly when targeting the theta/beta ratio and sensorimotor rhythm (SMR) (Wu et al., 2024; Zhang et al., 2024; Zhong et al., 2025). Specifically, neurofeedback protocols focusing on decreasing theta and increasing beta activity at frontal and central electrode sites have been shown to enhance cortical arousal and attentional stability (Himmelmeier & Werheid, 2024). Studies have further revealed that these neural changes are accompanied by improvements in behavioral regulation, working memory capacity, and cognitive flexibility (Louthrenoo et al., 2022; Shari et al., 2021).

A recent meta-analysis integrating over 40 randomized controlled trials found that neurofeedback significantly improved executive function indices—including working memory, cognitive planning, and response inhibition—in children with ADHD, with sustained effects at follow-up assessments (Zhong et al., 2025). Similarly, experimental work by Jounghani et al. demonstrated that neuromonitoring-guided interventions targeting working memory networks led to increased activation in the dorsolateral prefrontal cortex and enhanced performance on n-back tasks (Jounghani et al., 2024). These findings suggest that neurofeedback not only alleviates overt symptoms of hyperactivity and inattention but also facilitates underlying neural plasticity within cognitive control circuits.

Despite growing evidence, the heterogeneity in neurofeedback protocols, session structures, and electrode placements has resulted in variable outcomes across studies. For example, while theta/beta ratio training remains the most widely applied protocol, some studies have reported stronger effects using SMR training or slow cortical potential (SCP) regulation, depending on individual EEG profiles (Himmelmeier & Werheid, 2024). Personalized neurofeedback protocols—where training parameters are adjusted according to baseline EEG patterns—appear to produce better clinical results and higher engagement among participants (Kwon, 2023). In a randomized controlled trial, mobile neurofeedback applications also demonstrated feasibility and efficacy in improving attentional performance in children with ADHD, suggesting that digital delivery formats may enhance accessibility and adherence (Kwon, 2023).

E-ISSN: 3060-6713

The neural mechanisms underlying neurofeedback's therapeutic effects are believed to involve enhanced synchronization between prefrontal and parietal regions, improved dopaminergic regulation, and reinforcement of task-related neural patterns (Li et al., 2023). Moreover, neurofeedback may act synergistically with cognitive-behavioral and mindfulness-based interventions by promoting meta-awareness and attentional control (Hunkin et al., 2021). Evidence from meditation-based neurofeedback paradigms has shown that providing feedback on EEG markers of focused attention can improve state mindfulness and executive regulation (Hunkin et al., 2021). This convergence of findings supports the notion that neurofeedback fosters self-regulatory mechanisms crucial for sustained attention and goal-directed behavior—core deficits in ADHD (Barkley, 2015).

Neurofeedback has also been associated with long-term neurocognitive benefits. Follow-up assessments in several trials have indicated that improvements in attention and working memory persist for months after the cessation of training (Sheikh et al., 2022; Shojaei, 2024). This durability contrasts with the transient effects of pharmacological interventions, suggesting that neurofeedback may induce more permanent neurophysiological changes. A meta-analytic synthesis by Louthrenoo et al. confirmed that executive function gains achieved through neurofeedback remained stable across follow-up intervals of up to six months (Louthrenoo et al., 2022).

In the context of neurodevelopmental research, working memory and cognitive planning are central components of executive functioning that are disproportionately impaired in children with ADHD. Working memory, defined as the capacity to temporarily store and manipulate information, supports a range of cognitive operations including reasoning, problem-solving, and language comprehension (Kofler et al., 2024). Cognitive planning refers to the ability to formulate, organize, and execute goal-directed actions—functions largely governed by the prefrontal cortex (Viviani & Vallesi, 2021). Deficits in these domains contribute significantly to the everyday difficulties experienced by children with ADHD, such as disorganization, forgetfulness, and poor task completion (Barkley, 2015). Thus, targeting these functions through neurofeedback represents a neurocognitively grounded therapeutic strategy.

From a mechanistic standpoint, neurofeedback's ability to normalize EEG activity—particularly reductions in slow-wave (theta) activity and increases in fast-wave (beta) activity—correlates with improved prefrontal efficiency and executive control (Wu et al., 2024; Zhang et al., 2024). The modulation of the sensorimotor rhythm (12–15 Hz), associated with cortical inhibition and motor regulation, has been linked to reductions in hyperactivity and impulsivity (Himmelmeier & Werheid, 2024). Moreover, real-time reinforcement during neurofeedback may enhance attentional persistence and error monitoring through operant learning processes mediated by dopaminergic pathways (Yaghoobi Karimi et al., 2023).

Cross-cultural and technological innovations have expanded the applicability of neurofeedback across clinical and educational contexts. For instance, Yaghoobi Karimi et al. demonstrated that visual neurofeedback operating below the delta frequency range could modulate brain activity patterns in children with attentional difficulties, emphasizing the role of frequency-specific adjustments in optimizing treatment outcomes (Yaghoobi Karimi et al., 2023). Similarly, Jounghani et al.'s neuro-monitoring approach combined real-time EEG feedback with task performance metrics, offering a hybrid intervention that aligns with individualized neural signatures (Jounghani et al., 2024). These advancements highlight the movement toward precision neurofeedback—a paradigm shift from standardized to tailored interventions.

Nevertheless, methodological challenges remain in the field. Variability in sample sizes, lack of standardized control conditions, and inconsistencies in follow-up measurements have limited generalizability (Himmelmeier & Werheid, 2024). Furthermore, placebo (sham) neurofeedback studies have underscored the importance of controlling for expectancy and engagement effects (Wu et al., 2024). To ensure empirical rigor, contemporary trials now employ double-blind designs, automated feedback algorithms, and multimodal outcome measures integrating behavioral, neurophysiological, and imaging data (Zhong et al., 2025).

In Iran and other developing contexts, the growing interest in neurofeedback research reflects an effort to expand non-pharmacological treatment options for children with ADHD (Shari et al., 2021; Shojaei, 2024). These studies have documented significant improvements in attention regulation, cognitive flexibility, and overall executive functioning following neurofeedback training. Importantly, local adaptations of neurofeedback protocols have incorporated culturally appropriate feedback stimuli and parental engagement strategies, improving both acceptability and treatment compliance (Shojaei, 2024).

E-ISSN: 3060-6713

Despite these promising findings, the mechanisms by which neurofeedback enhances working memory and cognitive planning remain incompletely understood. It is not yet fully clear whether improvements result from direct modulation of specific neural oscillations or from broader enhancements in metacognitive awareness and attentional control. Moreover, evidence comparing neurofeedback's efficacy with pharmacological and behavioral interventions remains mixed, underscoring the need for further randomized controlled trials employing robust designs and follow-up assessments (Wu et al., 2024; Zhong et al., 2025).

Therefore, given the existing literature and the need for more empirical clarity, the present study was designed to examine the effectiveness of neurofeedback training on working memory performance and cognitive planning ability in children with Attention-Deficit/Hyperactivity Disorder (ADHD).

2. Methods and Materials

2.1. Study Design and Participants

This study was a randomized controlled clinical trial with a three-phase design (pretest, posttest, and follow-up). The statistical population consisted of children aged 7 to 14 years diagnosed with Attention-Deficit/Hyperactivity Disorder (ADHD), based on a structured clinical interview and the diagnostic criteria of the Diagnostic and Statistical Manual of Mental Disorders (5th ed.; DSM-5). Participants were recruited through convenience sampling from clients of the Shiva Psychological Clinic and referrals from collaborating schools in Rasht.

Inclusion criteria included an intelligence quotient (IQ) of 85 or higher, stable medication (if taking stimulant drugs) for at least four weeks prior to the study, and normal or corrected-to-normal vision and hearing. Exclusion criteria included uncontrolled epilepsy, severe comorbid neurodevelopmental disorders (e.g., autism spectrum disorder requiring substantial support), use of medications affecting electroencephalographic (EEG) activity (e.g., benzodiazepines or anticonvulsants), and uncorrected sensory impairments.

Assuming a medium effect size ($f \approx 0.25$), 95% confidence level, 80% statistical power, and an estimated dropout rate of 15%, the required sample size was calculated to be 70 participants (35 in each group). Eligible participants, after obtaining informed consent, were randomly assigned to either the active neurofeedback group or the sham control group. The main intervention consisted of 20 neurofeedback sessions conducted over 10 weeks (two sessions per week). Each session lasted 30 to 40 minutes and consisted of two training blocks of 15–20 minutes each, separated by a 3–5 minute rest. The sham protocol was identical to the active one in terms of the number and duration of sessions and the visual interface of the software, but the feedback provided was asynchronous and pre-recorded.

2.2. Measures

Conners' Rating Scale – Third Edition (Conners-3): The Conners-3, developed by Keith Conners (2008), is one of the most widely used tools for assessing ADHD symptoms in children and adolescents. It includes parent and teacher forms, containing 110 and 115 items respectively, rated on a 4-point Likert scale from 0 ("Not true at all") to 3 ("Completely true"). Raw scores are converted to standardized T-scores (mean = 50, SD = 10), covering key indices such as inattention, hyperactivity/impulsivity, executive function problems, learning problems, and the overall ADHD index. A reduction in T-scores at posttest indicates symptom improvement. The Persian version of the scale was standardized by Ebrahimi et al. (2015), showing satisfactory construct and criterion validity. Internal consistency for the main subscales in Iranian studies ranged between .79 and .91 (α = .87 for the parent form and α = .84 for the teacher form). In the present study, Cronbach's alpha for the total scale was .88, indicating good internal reliability and item homogeneity.

Digit Span Test: The Digit Span subtest from the *Wechsler Intelligence Scale for Children* (WISC, 2014) assesses verbal working memory and includes three parts: forward, backward, and sequencing. During the test, the examiner reads series of numbers at a steady pace, and the child must repeat them in the specified order. Raw scores are converted to scaled scores (mean = 10, SD = 3). Increases in posttest and follow-up scores reflect working memory improvement. The Persian version of the WISC was standardized in Iran by Karami-Nouri et al. (2017), with reliability coefficients for the Digit Span subtest ranging from .72 to .81. In this study, Cronbach's alpha for the combined subtest was .79, indicating acceptable internal reliability.

Corsi Block-Tapping Test (Visuospatial Working Memory): Originally developed by Philip Corsi (1972), this test measures visuospatial working memory capacity and short-term retention of nonverbal information. The task involves nine wooden blocks mounted irregularly on a board. The examiner taps sequences of blocks, and the participant must reproduce the sequence. The sequence length gradually increases to determine memory span. The main indices are "maximum correct sequence length" and "number of correct responses." International studies (e.g., Kessels et al., 2000) have reported test–retest reliability coefficients ranging from .75 to .82 and good convergent validity. The Persian version has been used in Iranian studies (e.g., Farahbakhsh, 2019), showing test–retest reliability of .78. In the present study, short-term test–retest reliability was .80, confirming temporal stability.

Tower of London Test (Cognitive Planning): The Tower of London test, developed by Tim Shallice (1982), is a standard tool for assessing cognitive planning and problem-solving skills. It consists of three vertical pegs and three colored balls; the participant must rearrange the balls from an initial configuration to a target configuration following specific movement rules. Assessment indices include the number of moves, solution time, number of errors, and total performance score. Persian and computerized versions have been used in Iranian research (e.g., Ebrahimi et al., 2018), demonstrating good construct validity and high sensitivity to prefrontal cortex dysfunction. Internationally, test–retest reliability coefficients have ranged from .71 to .85 (Culbertson & Zillmer, 2005). In this study, Cronbach's alpha for the total performance score was .83, and the test–retest reliability on a subsample of participants was .81, indicating good consistency and stability.

2.3. Intervention

Electrodes and Target Sites:

Block 1 (F4): Training focused on reducing the theta/beta ratio at F4 (right frontal lobe); reference A1/A2 (mastoids); ground electrode at FPz.

Block 2 (Cz/Frontal): Training aimed to increase sensorimotor rhythm (SMR, 12–15 Hz) and decrease theta (4–8 Hz) and delta (1–4 Hz) activity at Cz and the mid-frontal region (to enhance attentional stability and motor control).

Recording Settings: Impedance <10 kΩ (preferably <5 kΩ); high-pass filter at 0.5 Hz; low-pass filter at 40 Hz; notch filter at 50 Hz if necessary.

Feedback and Thresholds: Visual–auditory game-based feedback was provided with adaptive thresholds maintaining 60–70% success. If success exceeded 75% for 3–5 minutes, thresholds were increased; if below 55%, thresholds were readjusted and self-regulation strategies were taught.

Artifact Control: Ocular and muscular artifacts were monitored; feedback paused if electrooculographic (EOG) or electromyographic (EMG) thresholds were exceeded.

Session Monitoring: Percentage of time within threshold, thresholds, and band power indices were recorded per session. Additionally, a 3-minute baseline EEG (eyes open/closed) was obtained at sessions 1, 10, and 20.

Sham Control Group: The control group underwent the same number and duration of sessions; however, the feedback was asynchronous/pre-recorded and unrelated to participants' EEG signals. The environment, instructions, and therapist interactions were identical to the experimental condition to control for expectancy effects. After study completion, the control group was offered the opportunity to receive the real neurofeedback protocol.

2.4. Data Analysis

After data collection and initial screening for missing, outlier, and abnormal data, analyses were conducted using SPSS version 29 and, if needed, AMOS 4.3. Statistical assumptions were tested, including normality (Kolmogorov–Smirnov test, skewness, and kurtosis indices), homogeneity of variance (Levene's test), and independence of observations.

To compare changes in the dependent variables (working memory performance, cognitive planning ability, and ADHD symptom severity) across three time points (pretest, posttest, and follow-up) between the two groups (real neurofeedback and sham control), a mixed-design repeated measures ANOVA was performed. This allowed examination of within-subject effects (time), between-group effects (intervention type), and interaction effects. If the sphericity assumption was violated, the Greenhouse–Geisser correction was applied to adjust degrees of freedom.

To control for potential covariates (age, gender, baseline IQ, and initial symptom severity), a complementary multivariate analysis of covariance (MANCOVA) was conducted. Bonferroni post hoc tests were used for pairwise comparisons to control for Type I error. Effect sizes were calculated using partial eta squared ($\eta^2 p$) and Cohen's d to determine the magnitude of changes.

Additionally, clinically significant changes in Conners scores were analyzed using the Reliable Change Index (RCI) and response rate (≥10 T-score reduction). For all statistical analyses, a significance level of $p < .05$ was considered, and

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values between .05 and .10 were interpreted as statistical trends.

3. Findings and Results

In this section, descriptive and inferential findings are reported.

Table 1

Mean and Standard Deviation of the Research Variables Across Three Measurement Phases

Variable	Group	Pretest (Mean ± SD)	Posttest	Follow-up
Verbal Working Memory	Neurofeedback	8.4 ± 1.5	10.6 ± 1.3	10.2 ± 1.4
	Control	8.3 ± 1.4	8.6 ± 1.5	8.5 ± 1.4
Visuospatial Working Memory	Neurofeedback	5.2 ± 0.8	6.4 ± 0.9	6.3 ± 0.8
	Control	5.1 ± 0.9	5.3 ± 0.8	5.2 ± 0.9
Cognitive Planning	Neurofeedback	16.8 ± 3.1	22.7 ± 2.9	21.9 ± 2.7
	Control	17.1 ± 3.0	18.2 ± 3.2	18.0 ± 3.1
ADHD Index	Neurofeedback	71.5 ± 7.2	58.4 ± 6.5	59.6 ± 6.9
	Control	72.2 ± 6.8	69.8 ± 6.4	69.1 ± 6.7

This table presents the mean and standard deviation of the main variables at the pretest, posttest, and follow-up phases. It can be observed that the neurofeedback group showed a consistent improvement in working memory, cognitive planning, and reduction of ADHD symptoms, whereas the control group exhibited no significant changes.

Table 2

Results of Repeated Measures ANOVA for Within-Group, Between-Group, and Interaction Effects

Variable	Effect	F	df	p	Effect Size (η²p)
Verbal Working Memory	Time	42.8	2, 66	< .001	.56
	Group	18.7	1, 33	< .001	.36
	Time × Group	31.9	2, 66	< .001	.49
Visuospatial Working Memory	Time	25.4	2, 66	< .001	.43
	Group	10.1	1, 33	.003	.23
	Time × Group	19.2	2, 66	< .001	.37
Cognitive Planning	Time	59.3	2, 66	< .001	.64
	Group	22.8	1, 33	< .001	.41
	Time × Group	38.1	2, 66	< .001	.52
ADHD Index	Time	78.9	2, 66	< .001	.70
	Group	29.5	1, 33	< .001	.47
	Time × Group	45.2	2, 66	< .001	.58

The results indicate that the main effects of time, group, and their interaction were statistically significant for all variables. In particular, the time × group interaction revealed that changes in the neurofeedback group were significantly greater than those in the control group.

Table 3

Pairwise Mean Comparisons in the Neurofeedback Group (Bonferroni Test)

Variable	Comparison	Mean Difference ± SE	p	Cohen's d
Verbal Working Memory	Pre → Post	2.2 ± 0.4	< .001	1.45
	Post → Follow-up	−0.4 ± 0.3	.21	0.23
Visuospatial Working Memory	Pre → Post	1.2 ± 0.3	< .001	1.18
Cognitive Planning	Pre → Post	5.9 ± 0.7	< .001	1.98
ADHD Index	Pre → Post	−13.1 ± 1.4	< .001	1.76

The Bonferroni post hoc test showed that the differences between pretest and posttest scores were statistically significant for all variables in the neurofeedback group. At follow-up, a slight decrease in the effects was observed;

E-ISSN: 3060-6713

however, the differences from the posttest were not statistically significant, indicating relative stability of the treatment effects over time.

Table 4

Clinical Response Index Based on Conners Score Change

Group	n	Percentage of Responders (≥10 T-score reduction)	Mean Score Change ± SD	95% CI	χ^2	p
Neurofeedback	34	76.5%	−13.1 ± 6.5	[−15.2, −10.9]	14.3	< .001
Control	34	14.7%	−3.1 ± 5.9	[−5.3, −0.9]		

Based on the Reliable Change Index (RCI), more than three-quarters of the children in the neurofeedback group showed a clinically significant reduction in ADHD symptom severity, whereas less than 15% of the control group achieved such improvement. The difference between the two groups was statistically highly significant.

4. Discussion and Conclusion

The findings of this randomized controlled trial revealed that neurofeedback training significantly improved verbal and visuospatial working memory, cognitive planning, and reduced ADHD symptom severity among children aged 7–14 years diagnosed with Attention-Deficit/Hyperactivity Disorder. These improvements were evident both immediately after the intervention and were maintained at the follow-up stage, suggesting that neurofeedback produces durable neurocognitive benefits beyond temporary behavioral changes. The significant time × group interactions across all dependent variables indicate that the observed gains were specifically attributable to neurofeedback training rather than general test–retest effects or placebo-related improvements.

The substantial enhancement in verbal and visuospatial working memory observed in the neurofeedback group aligns with a growing body of literature supporting the effectiveness of neurofeedback in enhancing executive functions among children with ADHD. Working memory is a critical executive function associated with prefrontal cortical activity and fronto-parietal network integrity. Numerous studies have documented that neurofeedback, particularly protocols focusing on theta/beta ratio reduction and SMR enhancement, can improve working memory capacity by normalizing abnormal EEG oscillations (Kofler et al., 2024; Wu et al., 2024). The results of the present study corroborate these findings, demonstrating significant post-intervention gains in both verbal and visuospatial working memory measures, with large effect sizes. Similarly, in a neuromonitoring-guided intervention, Jounghani and colleagues observed notable increases in dorsolateral prefrontal cortex activation, accompanied by improvements in n-back task performance following neurofeedback training (Jounghani et al., 2024). This suggests that neurofeedback facilitates neural plasticity within cortical regions associated with information manipulation and attention regulation.

The improvement in working memory observed here also resonates with evidence from meta-analyses indicating that neurofeedback produces moderate-to-large effects on cognitive performance in ADHD populations. Louthrenoo et al. synthesized multiple controlled trials and reported significant improvements in executive functioning domains, including working memory and inhibitory control, following neurofeedback (Louthrenoo et al., 2022). Similarly, the meta-analysis conducted by Zhong et al. confirmed that neurofeedback interventions are effective in enhancing both behavioral and cognitive indices of ADHD, emphasizing their long-term benefits (Zhong et al., 2025). The present findings extend these results by demonstrating not only immediate post-intervention improvements but also sustained effects at follow-up, underscoring the persistence of neurofeedback-induced neural changes.

Moreover, the increase in cognitive planning ability observed among participants aligns with prior studies that have identified planning deficits as a hallmark of ADHD-related executive dysfunction (Barkley, 2015). The significant post-training gains in Tower of London task performance suggest that neurofeedback strengthens prefrontal cortical regulation responsible for goal-directed behavior and sequencing. This is consistent with previous evidence showing that neurofeedback enhances functional connectivity between the prefrontal cortex and subcortical structures (Himmelmeier & Werheid, 2024; Viviani & Vallesi, 2021). The observed effect sizes (η^2p ranging from .43 to .70) indicate a strong relationship between neurofeedback training and improvements in higher-order cognitive control processes. These findings mirror those of Shari et al., who reported significant improvements in cognitive flexibility and executive function among students undergoing neurofeedback training (Shari et al., 2021).

Another major finding of this study was the significant reduction in ADHD symptom severity following neurofeedback training, with over 76% of participants achieving clinically meaningful reductions on the Conners scale (≥10 T-score points). This result supports the conclusions of several meta-analyses demonstrating the therapeutic value of neurofeedback for reducing hyperactivity, inattention, and impulsivity (Wu et al., 2024; Zhang et al., 2024). Wu et al. conducted a network meta-analysis comparing various neurofeedback modalities and concluded that theta/beta ratio training and SMR training were among the most effective for ADHD symptom reduction. Similarly, Zhang et al. found that neurofeedback interventions yielded comparable or superior efficacy relative to pharmacotherapy in symptom alleviation, particularly when applied over multiple weeks with individualized feedback protocols (Zhang et al., 2024).

The sustained improvements observed at the follow-up phase indicate that neurofeedback may induce enduring neurophysiological adaptations rather than transient behavioral effects. This finding is consistent with longitudinal studies showing that neurofeedback produces long-term modulation in cortical oscillatory activity, contributing to stable improvements in attention and executive functioning (Sheikh et al., 2022; Shojaei, 2024). In Shojaei's randomized study on Iranian elementary students, neurofeedback led to significant and lasting symptom reduction in inattention and hyperactivity, suggesting durable cortical reorganization. Sheikh and colleagues also reported that neurofeedback produced stable enhancements in motor control and attentional performance, accompanied by reductions in anxiety and sleep problems among children with ADHD (Sheikh et al., 2022). The current results corroborate these outcomes, showing both cognitive and behavioral improvements that persisted weeks after the completion of training.

Mechanistically, these improvements can be attributed to neurofeedback's capacity to regulate cortical oscillations associated with attentional and executive processes. ADHD is characterized by elevated theta activity and reduced beta activity, reflecting cortical underarousal and poor inhibitory control (Barkley, 2015; Kofler et al., 2024). Neurofeedback directly targets these abnormalities by reinforcing faster beta oscillations and suppressing slow theta rhythms, thereby enhancing cortical activation and information processing efficiency (Himmelmeier & Werheid, 2024). The present study's protocol—reducing the theta/beta ratio at F4 and enhancing SMR at Cz—was particularly effective, supporting prior evidence that fronto-central training optimizes attention and response inhibition (Louthrenoo et al., 2022). Additionally, Yaghoobi Karimi et al. found that modulation of delta-range visual neurofeedback could effectively alter cortical excitability patterns in children, highlighting the potential of frequency-specific interventions (Yaghoobi Karimi et al., 2023).

The clinical efficacy observed in this study may also stem from neurofeedback's reinforcement-based learning mechanism. By providing real-time auditory and visual feedback, participants learn to self-regulate neural activity patterns associated with improved attention and reduced impulsivity (Hunkin et al., 2021). Evidence from meditation-based neurofeedback studies supports this model, demonstrating that feedback-driven modulation of EEG markers enhances mindfulness and attentional control (Hunkin et al., 2021). Neurofeedback thus operates at the intersection of cognitive training and neuroplasticity, promoting adaptive regulation of prefrontal activity through reward-based feedback loops (Viviani & Vallesi, 2021).

Importantly, the use of individualized adaptive thresholds in the current neurofeedback protocol likely enhanced training efficiency. This personalization element is increasingly recognized as a critical factor in optimizing neurofeedback outcomes. Himmelmeier and Werheid emphasized that adaptive threshold adjustments and individualized frequency targeting improve treatment responsiveness by aligning feedback contingencies with participants' unique EEG patterns (Himmelmeier & Werheid, 2024). Likewise, Kwon's mobile neurofeedback trial demonstrated that portable, personalized training systems could achieve comparable symptom reduction to laboratory-based systems while improving adherence and ecological validity (Kwon, 2023). The strong retention of therapeutic effects observed in the present study likely reflects the benefits of such dynamic, participant-specific training designs.

Moreover, neurofeedback's impact extends beyond cognitive enhancement to emotional and behavioral regulation. ADHD symptoms often co-occur with emotional dysregulation, anxiety, and motivational difficulties (Barkley, 2015). Through its self-regulatory learning framework, neurofeedback may enhance emotion control by stabilizing neural oscillations linked to the limbic-prefrontal

E-ISSN: 3060-6713

circuitry. Studies have demonstrated that reductions in theta activity are associated with decreased emotional volatility and improved self-monitoring (Li et al., 2023). Therefore, improvements in executive functions observed in this study may represent both cognitive and affective regulation gains, further explaining the general symptom reduction observed in the Conners scores.

While the majority of previous studies have focused on short-term cognitive outcomes, this study's inclusion of a follow-up assessment allowed evaluation of long-term maintenance of benefits. Consistent with prior longitudinal evidence, the absence of significant decline from posttest to follow-up underscores the stability of neurofeedback effects. Zhong et al. and Louthrenoo et al. similarly reported that executive function improvements remained robust at 3–6 months post-intervention (Louthrenoo et al., 2022; Zhong et al., 2025). Such durability supports the hypothesis that neurofeedback fosters enduring neural reorganization rather than temporary compensatory strategies.

Collectively, these findings reinforce the conceptualization of neurofeedback as a neuromodulatory approach capable of producing both neurophysiological and behavioral improvements. The convergence between the present study's results and those of recent systematic reviews highlights neurofeedback's growing empirical foundation (Wu et al., 2024; Zhang et al., 2024; Zhong et al., 2025). Importantly, the study contributes new evidence from an Iranian sample, extending generalizability to non-Western populations and underscoring neurofeedback's cross-cultural efficacy (Shojaei, 2024). The observed stability of effects, large effect sizes, and clinically meaningful symptom reduction together support neurofeedback as a promising adjunctive or alternative intervention for children with ADHD.

Despite its robust findings, the present study is subject to several limitations that warrant consideration. First, although a randomized controlled design was employed, the sample size was relatively modest, limiting statistical power for subgroup analyses (e.g., gender or medication status). Second, the study relied primarily on behavioral and neuropsychological outcome measures, while neuroimaging or quantitative EEG data could have provided more direct evidence of neural changes underlying the observed cognitive improvements. Third, although efforts were made to ensure blinding in the sham control condition, complete elimination of expectancy effects may not have been achieved, as participants might have inferred their group allocation. Fourth, the follow-up period was relatively short; long-term maintenance of improvements beyond several months remains to be determined. Finally, while the neurofeedback protocol was standardized, future studies might benefit from incorporating individualized frequency targeting or multimodal training to optimize outcomes further.

Future investigations should consider larger, multisite samples to increase generalizability and statistical precision. Incorporating neuroimaging techniques such as functional MRI or source-localized EEG could elucidate the neural mechanisms underlying the observed behavioral and cognitive gains. Moreover, comparative studies examining neurofeedback in combination with pharmacological or cognitive-behavioral interventions could clarify potential synergistic effects. Longitudinal designs with follow-up periods exceeding one year are recommended to assess the durability of neural and cognitive changes. Researchers should also explore the role of participant characteristics—such as baseline EEG profiles, age, and comorbidities—in moderating neurofeedback responsiveness. Finally, advancements in mobile and gamified neurofeedback systems merit exploration as cost-effective and scalable solutions for use in schools and clinical settings.

Clinicians and educators may consider integrating neurofeedback as part of a multimodal intervention framework for children with ADHD, complementing behavioral and educational therapies. Tailoring neurofeedback protocols to individual EEG profiles can enhance efficacy and engagement. Training practitioners to monitor progress through both behavioral and electrophysiological indicators can ensure adaptive adjustment of protocols. Furthermore, implementing parent education and follow-up support sessions may strengthen the maintenance of training effects at home and school environments. Neurofeedback, when applied systematically and in conjunction with psychosocial support, holds substantial promise as a safe, non-invasive, and sustainable approach to improving attention regulation and executive functioning in children with ADHD.

Authors' Contributions

Authors contributed equally to this article.

Declaration

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

E-ISSN: 3060-6713

Transparency Statement

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

Acknowledgments

We would like to express our gratitude to all individuals helped us to do the project.

Declaration of Interest

The authors report no conflict of interest.

Funding

According to the authors, this article has no financial support.

Ethics Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants.

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E-ISSN: 3060-6713