

The Effects of Exergaming and Neurofeedback on Working Memory in Children with Attention-Deficit/Hyperactivity Disorder

Majid. Heydarian¹, Afkham. Daneshfar^{2*}, Masoumeh. Shojaei², Keyvan. Molanorouzi³

¹ PhD Student, Department of Sport Science, SR.C., Islamic Azad University, Tehran, Iran

² Department of Motor Behavior, Faculty of Sport Sciences, Alzahra University, Tehran, Iran

³ Department of Sport Science, SR.C., Islamic Azad University, Tehran, Iran

* Corresponding author email address: a.daneshfar@alzahra.ac.ir

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ABSTRACT

This study aimed to compare the immediate and sustained effects of neurofeedback and exergaming on working memory in children with attention-deficit/hyperactivity disorder. This applied experimental study used a randomized pretest–posttest–follow-up design with four groups. The participants were 52 boys aged 7–10 years with attention-deficit/hyperactivity disorder who attended mainstream primary schools in Qazvin, Iran. After ensuring the homogeneity of the groups regarding intelligence and selected demographic characteristics, participants were randomly assigned to neurofeedback, sham neurofeedback, exergaming, and control groups. The neurofeedback and exergaming groups each included 14 participants, whereas the sham neurofeedback and control groups each included 12 participants. The intervention groups completed 30 sessions, conducted three times per week for 45 minutes. Working memory was assessed using the computerized N-Back Task at pretest, posttest, and one-month follow-up. Data were analyzed using a two-factor mixed analysis of variance and pairwise comparisons adjusted using the Bonferroni correction with the bootstrap procedure. The main effect of time on working memory was significant, $F(2, 96) = 53.04$, $p < .001$, $\eta^2p = .52$. The main effect of group was also significant, $F(3, 48) = 3.66$, $p = .019$, $\eta^2p = .18$, and the time-by-group interaction was significant, $F(6, 96) = 15.07$, $p < .001$, $\eta^2p = .48$. At posttest, neurofeedback produced significantly greater improvement than sham neurofeedback ($p = .018$) and control ($p = .010$), while exergaming outperformed control ($p = .002$). At follow-up, neurofeedback remained superior to sham neurofeedback ($p = .001$) and control ($p = .004$), and exergaming remained superior to control ($p = .001$). No significant differences were found between neurofeedback and exergaming at posttest or follow-up. Both neurofeedback and exergaming produced significant and sustained improvements in working memory among children with attention-deficit/hyperactivity disorder, with no significant difference between the two active interventions. These findings support the use of both interventions as viable, evidence-based non-pharmacological options for enhancing working memory in this population.

Keywords: Active video games, attention-deficit/hyperactivity disorder, children, EEG biofeedback, executive functions, interactive digital games, working memory

1. Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a neurodevelopmental condition characterized by developmentally inappropriate and persistent patterns of inattention, hyperactivity, and impulsivity that interfere with academic, social, behavioral, and family functioning. The conceptualization and diagnostic boundaries of ADHD have evolved considerably over time, reflecting changes in clinical knowledge regarding symptom presentation, developmental course, functional impairment, and the heterogeneity of the disorder. Contemporary diagnostic approaches recognize that ADHD is not merely a behavioral problem but a complex condition involving deficits in cognitive control, self-regulation, motivational processing, and executive functions (Adam & Young-Walker, 2014). ADHD commonly begins in childhood and can affect children's capacity to follow instructions, organize schoolwork, maintain attention, regulate motor activity, wait for rewards, and adapt their behavior to environmental demands. These difficulties may persist across developmental stages and contribute to poor educational achievement, strained peer and family relationships, reduced self-esteem, and increased vulnerability to emotional and behavioral problems (Betancourt et al., 2024; Faraone et al., 2021; Peterson et al., 2024; Spender et al., 2023).

Epidemiological evidence indicates that ADHD is one of the most prevalent neurodevelopmental disorders among school-aged children. Although prevalence estimates vary according to diagnostic criteria, informants, assessment procedures, geographical setting, and methodological quality, international evidence suggests that ADHD has remained a substantial public health and educational concern across recent decades (Polanczyk et al., 2014). Research conducted among primary school populations has similarly demonstrated that symptoms of inattention, hyperactivity, and impulsivity are frequently recognized by both parents and teachers, although estimated prevalence can differ depending on the perspective of the informant and the criteria used to define clinically significant symptoms (Arjmandi et al., 2015). The high prevalence of ADHD in primary-school settings is especially important because this developmental period places increasing demands on sustained attention, behavioral inhibition, memory, planning, and goal-directed learning. When these capacities are impaired, children may experience cumulative disadvantages in academic learning and classroom participation.

The functional consequences of ADHD cannot be understood solely through observable behavioral symptoms. Neuropsychological research has shown that children with ADHD often exhibit weaknesses in executive functions, including inhibitory control, sustained attention, planning, cognitive flexibility, processing speed, and working memory. Neuropsychological assessment is therefore important for clarifying how cognitive deficits contribute to children's everyday functioning and for identifying intervention targets that may not be captured adequately through behavioral symptom ratings alone (Pritchard et al., 2012). Among executive functions, working memory is particularly important because it enables individuals to temporarily maintain, update, and manipulate information while performing an ongoing task. It supports reading comprehension, mathematical reasoning, problem solving, following multistep instructions, note-taking, classroom participation, and the regulation of behavior in accordance with current goals (Cole et al., 2024).

Working-memory deficits may be especially disruptive for children with ADHD because many classroom activities require the simultaneous processing and retention of information. A child may need to remember the teacher's instructions while beginning an assignment, retain intermediate steps while solving a mathematical problem, or monitor previous responses while adjusting behavior to changing task requirements. When working-memory capacity is limited, information may be lost before it can be used, resulting in incomplete tasks, careless errors, difficulty following instructions, and apparent inattentiveness. These difficulties can also intensify frustration and avoidance, particularly when the child is repeatedly exposed to tasks that exceed cognitive capacity (Gray et al., 2012).

Treatment of ADHD commonly involves pharmacotherapy, behavioral interventions, parent training, educational accommodations, cognitive rehabilitation, or combinations of these approaches. Stimulant medication is among the most established treatments and can produce meaningful reductions in core ADHD symptoms. Evidence-based pharmacological guidelines nevertheless emphasize the need for individualized treatment selection, monitoring of adverse effects, consideration of comorbidities, and integration of medication with psychosocial and educational support when appropriate (Bolea-Alamanac et al., 2014).

Despite the effectiveness of medication for many children, interest in nonpharmacological interventions has increased because of concerns regarding side effects, incomplete symptom response, treatment adherence,

parental preference, and the need to target cognitive processes directly. Neurofeedback is one of the most extensively investigated technology-based interventions for ADHD. Comparative studies have found that both neurofeedback and medication may improve ADHD-related difficulties, although their mechanisms, immediacy, durability, and acceptability may differ (Mohammadi & Hosseini, 2018). Neurofeedback is a form of operant conditioning in which individuals receive real-time information about aspects of their brain activity and learn, through repeated reinforcement, to modify targeted patterns of neural activation. The historical and technical foundations of neurofeedback were developed through work demonstrating that electroencephalographic activity could be shaped through feedback and reinforcement (Sterman & Egner, 2006). During neurofeedback sessions, brain signals are recorded through scalp electrodes, processed by specialized software, and translated into visual or auditory feedback. Desired brain-activity patterns are rewarded through progress in a game, animation, or sound, whereas feedback is reduced or interrupted when activity moves away from the target range (Westwood et al., 2025).

Neurofeedback training has been reported to improve sustained attention and working memory in primary-school boys with ADHD (Dasht Bozorgi et al., 2016). Studies combining neurofeedback with computerized cognitive exercises have also found improvements in working memory, suggesting that the simultaneous targeting of brain regulation and task-specific cognitive practice may produce complementary benefits (Heidari Nasab et al., 2016). Research has additionally reported reductions in hyperactivity and attention-deficit symptoms following neurofeedback among school students and young adults (Narimani et al., 2013; Seilsapour et al., 2015). Case-based evidence has similarly indicated that repeated neurofeedback training may strengthen neuronal self-regulation in individuals with attention-deficit symptoms (Fauzan & Nazaruddin, 2012). The proposed relevance of neurofeedback for ADHD is based on evidence that altered patterns of cortical activation and self-regulation may contribute to attentional and executive-function difficulties. Neurofeedback protocols aim to enhance the child's capacity to regulate brain activity associated with attention, inhibition, and cognitive control. Theoretical and clinical literature has described neurofeedback as a potentially valuable intervention for ADHD while emphasizing the importance of standardized protocols, adequate training intensity, appropriate control conditions, and valid outcome

assessment (Heinrich et al., 2016). Clinical reviews have generally concluded that neurofeedback may reduce ADHD symptoms and improve selected neuropsychological outcomes, but they have also highlighted variability in protocol type, blinding, control conditions, and the specificity of treatment effects (Holtmann et al., 2014). Questions regarding specificity are particularly important because improvement may partly reflect repeated practice, therapist attention, expectancy, motivation, or exposure to computer-based training rather than direct regulation of neural activity (Brandeis, 2011).

Meta-analytic evidence from randomized controlled trials has suggested that neurofeedback can produce improvements in clinical and neuropsychological outcomes among children with ADHD, although effect sizes may differ according to outcome informant, methodological rigor, and control condition (Cortese et al., 2016). More recent systematic review and meta-analytic evidence specifically focused on executive functioning has strengthened the rationale for examining neurofeedback as a means of improving cognitive control in children with ADHD (Zhong et al., 2025). Nevertheless, the literature remains heterogeneous, and not all studies have demonstrated clear superiority over active comparison treatments. For example, a randomized trial comparing neurofeedback with stimulant medication and physical activity found that the relative effects of these interventions depended on the particular cognitive outcome examined (Gelade et al., 2016). Such findings indicate that neurofeedback should be evaluated not only against no-treatment controls but also against credible sham and active interventions. In line with this, a systematic review found heterogeneous evidence for neurofeedback training efficacy on working memory in ADHD (Doulou et al., 2026). While small non-randomized studies reported improvements, a large randomized controlled trial showed no advantage over treatment as usual. This inconsistency may stem from variations in neurofeedback protocols, working memory assessment tasks, and study designs (Doulou et al., 2026; Zhong et al., 2025). Reviews of the field have therefore regarded neurofeedback as a promising treatment, while noting that conclusions depend on training protocol, sample characteristics, outcome selection, and methodological quality (Nemati & Alizadeh, 2017).

Recent developments have expanded neurofeedback beyond conventional ADHD protocols. Reviews across neurological and psychiatric conditions describe biofeedback and neurofeedback as increasingly adaptable

clinical technologies, while stressing the need for protocol-specific evidence and appropriately controlled trials (Melo et al., 2025). Different electroencephalographic protocols may produce distinct clinical effects, as illustrated by comparative research on sensory-motor rhythm and alpha-theta neurofeedback (Lotfinia et al., 2025). Neurofeedback has also been examined in relation to depression and anxiety through real-time functional magnetic resonance imaging (Zhang et al., 2025), in combination with mindfulness meditation using consumer-grade systems (Treves et al., 2025), and for the enhancement of self-regulation and performance in sport contexts (Yu et al., 2025). These broader applications support the general principle that feedback-based training may strengthen learned regulation of cognitive, emotional, and physiological states, although findings from one clinical population cannot be assumed to transfer directly to another.

Multicomponent interventions have also emerged. A recent approach combining respiratory biofeedback, neurofeedback, and median nerve stimulation reported beneficial effects among children with ADHD, illustrating growing interest in nonpharmacological protocols that engage several regulatory systems simultaneously (Santamaría-Vázquez et al., 2025). Reviews focused on children and adolescents with ADHD and learning disabilities likewise suggest that neurofeedback may improve executive and academic functions, although stronger studies are required to determine the durability and practical significance of these gains (Sadeghi Ahouei et al., 2025). The question of durability is particularly important because immediate post-intervention improvement may reflect short-term task familiarity, whereas meaningful rehabilitation requires that gains persist after structured training has ended.

Computerized working-memory training has been investigated as one method of directly strengthening the cognitive processes. Evidence from children and adolescents with learning disabilities and comorbid ADHD suggests that structured computerized training may improve aspects of working memory and attention, although the extent to which gains generalize to academic performance and everyday behavior remains an important question (Gray et al., 2012). Movement-based computerized cognitive rehabilitation has also been proposed as a means of improving working memory through the integration of cognitive demands and physical activity. Such interventions require children to process visual information, update task rules, inhibit incorrect responses, and coordinate movement with rapidly

changing stimuli. Research on movement-based computerized rehabilitation has reported improvements in working-memory performance among children with ADHD, suggesting that cognitive engagement may be enhanced when training is presented through interactive physical activities rather than repetitive sedentary behaviors (Jalili et al., 2019). Computer-based cognitive rehabilitation has also been associated with improvements in behavioral and executive-function outcomes, including attention, inhibitory control, and risk-related decision-making (Nazerieh & Niknam, 2024). More recent tele-cognitive rehabilitation findings further indicate that targeted attention training can improve executive functions and reduce behavioral symptoms among children with ADHD, supporting the adaptability of game-based and technology-assisted approaches across clinical and home-based contexts (Nejati & Derakhshan, 2024).

Exergaming represents another promising nonpharmacological approach. Exergames are interactive digital games or active video games that require body movements to control game events. Motion-sensitive systems, including camera-based and sensor-based consoles, permit the child's movements to be captured and translated into actions on a screen. Unlike conventional sedentary games, exergames combine physical activity with cognitive stimulation, immediate feedback, goal pursuit, and reward. Studies of video game play have shown that these games can engage attention, memory, visuospatial processing, and executive control, although benefits depend on game characteristics, training intensity, and the similarity between practiced and assessed cognitive processes (Boot et al., 2008). The motivational structure of games may also be important. Anticipation, prediction, feedback, and reward contribute to sustained engagement and influence how individuals respond to unfolding events (Huron, 2007). In children with ADHD, whose attention and persistence may decline during monotonous tasks, the immediate and repeated feedback provided by exergames may increase adherence to cognitively demanding practice.

Exergaming may improve executive function through several interacting mechanisms. Physical exercise can increase physiological arousal, cerebral blood flow, and activation of neural systems involved in attention and cognitive control. Simultaneously, the game requires the child to monitor stimuli, remember instructions, inhibit premature actions, coordinate movements, and adapt to changing rules. Xbox Kinect-based interventions have been shown to facilitate movement performance in children with

motor difficulties, demonstrating that motion-controlled gaming can support structured, repetitive, and progressively challenging practice (Rostamipour et al., 2019). For children with ADHD, these features may be particularly useful because cognitive training is embedded within an engaging activity that limits prolonged sitting and converts repeated practice into goal-oriented play.

Controlled studies have increasingly examined exergaming in ADHD populations. A randomized controlled trial found that exergaming improved attention in children with ADHD, supporting the use of cognitively demanding physical games as a therapeutic tool (Ji et al., 2023). Exercise training delivered through a hit-sport-game format has also been associated with improvements in self-control and regulation among children with ADHD (Salleg-Cabarcas et al., 2024). These findings suggest that interactive exercise training may influence not only physical fitness but also executive processes central to behavioral regulation. However, the potential benefits of digital games must be distinguished from problematic or excessive gaming. Video game addiction has been associated with anxiety, depression, and ADHD-related characteristics in children and adolescents, indicating that therapeutic gaming should be structured, supervised, time-limited, and directed toward specific developmental goals (Alrahili et al., 2023).

Although both neurofeedback and exergaming have been linked to improvements in attention and executive functions, direct comparisons between these interventions remain limited. Neurofeedback focuses primarily on learned regulation of electrophysiological activity, whereas exergaming combines cognitive challenge with whole-body physical activity, sensory feedback, reward, and motor coordination. Both may improve working memory, but they may operate through partly different mechanisms. Moreover, many previous studies have used only pretest–posttest designs, have lacked sham conditions, or have not assessed whether treatment gains remain after the intervention. Inclusion of a sham neurofeedback group is particularly valuable because it helps separate the specific effects of contingent brain-based feedback from expectancy, therapist contact, and participation in an apparently active computerized treatment. A no-intervention control group provides an additional basis for evaluating changes that might otherwise result from maturation, repeated testing, or ordinary educational experience.

The present study therefore addressed several methodological and practical gaps by comparing active neurofeedback, sham neurofeedback, exergaming, and a

control condition within a randomized pretest–posttest–follow-up design. Working memory was selected as the primary outcome because of its central role in executive functions, academic performance, and everyday self-regulation among children with ADHD. Evaluating both immediate and one-month follow-up effects made it possible to determine whether changes were temporary or sustained. Furthermore, comparing neurofeedback with exergaming provided evidence regarding whether one technology-based nonpharmacological intervention was more effective than the other or whether both represented viable approaches for strengthening working memory in children with ADHD. Accordingly, the aim of the present study was to compare the immediate and sustained effects of neurofeedback and exergaming on the working memory of children with attention-deficit/hyperactivity disorder.

2. Methods and Materials

2.1. Study Design and Participants

This applied study employed a randomized experimental design with pretest, posttest, and one-month follow-up assessments. The study included two active intervention groups receiving neurofeedback training and exergaming, respectively, a sham-intervention group receiving noncontingent neurofeedback, and a no-intervention control group. Before the interventions began, working memory was assessed in all four groups using the N-Back Task. Participants randomly assigned to the four groups. The intervention and sham groups completed 30 training sessions, conducted three times per week, with each session lasting approximately 45 minutes. The control group did not receive any intervention during the study period and continued its usual educational and daily activities. Immediately after completion of the 30 sessions, working memory was reassessed in all groups under conditions comparable to those used at baseline. A follow-up assessment was conducted one month after the final intervention session to determine whether any observed changes in working memory were maintained over time.

The participants of the present study were 52 children aged 7 to 10 years with ADHD, who were selected from the statistical population of male students in Grades 1 through 4 of mainstream primary schools in Qazvin, Iran, during the 2021–2022 academic year. The required sample size was estimated using G*Power version 3.1.9.7. The mean age, height, and weight were 8.65 years ($SD=1.2$), 133.9 cm ($SD=6.3$), and 29.9 kg ($SD=4.2$), respectively. Participants

were comparable in terms of demographic characteristics, e.g., socioeconomic status (moderate) and intellectual functioning (IQ: 80–129), thereby ensuring homogeneity across the study groups. Then, participants were randomly assigned to the neurofeedback group (n=14); the sham neurofeedback group (n=12); the exergaming group (n=14); or the control group (n=12). Eligibility was determined on the basis of the target age range, enrollment in a mainstream primary school, identification of ADHD by a psychiatrist after screening, adequate intellectual functioning for understanding and completing the tasks, physical capacity to participate in the movement-based intervention, and willingness of the child and parents to cooperate throughout the study. Children with comorbid and serious neurological disorders, severe sensory or motor impairments, or medical conditions that could interfere with neurofeedback or exergaming activities were not included. Participants who were repeatedly absent from the intervention sessions, initiated another structured cognitive intervention during the study, or were unable to complete the posttest or follow-up assessment were considered eligible for withdrawal from the study. The study procedures were explained to the parents and children in age-appropriate language, and participation was voluntary. Confidentiality of the participants' personal information and test results was maintained throughout the research process. Written informed consent was obtained from the parents after they had been informed of the methodology and the associated ethical considerations.

2.2. Measures

Working memory was measured using the N-Back Task, a computerized cognitive task originally introduced by Kirchner in 1958 for evaluating executive functions and the continuous monitoring and updating of information. The task is particularly appropriate for assessing working memory because successful performance requires participants not only to retain recently presented information but also to compare and manipulate that information as new stimuli are presented. It is also regarded as relatively independent of language and cultural background because performance is primarily based on the rapid processing and comparison of visual stimuli. In the version used in the present study, 100 visual stimuli were presented consecutively on a computer screen at intervals of approximately 1,800 milliseconds. For each stimulus, the participant was required to compare the current item with the immediately preceding item. When the child identified the

current stimulus as matching the preceding stimulus, the number-one key was pressed; when no match was identified, the number-two key was pressed. Before formal administration, the instructions were explained clearly, and participants were given an opportunity to ensure that they understood the response procedure. The task required approximately two to three minutes to complete. The computerized program recorded the number of correct and incorrect responses, which provided objective indicators of working-memory performance. Higher numbers of correct responses and lower numbers of incorrect responses represented better performance. The same task and administration procedure were used during the pretest, posttest, and one-month follow-up assessments to permit comparison of changes across time and between the four study groups.

2.3. Interventions

The neurofeedback intervention was conducted in a designated room equipped with an electroencephalographic recording and neurofeedback system connected to a computer. Before the beginning of the intervention, participants and their parents were formally informed of the session schedule, and a trained neurofeedback specialist explained the procedure and familiarized each child with the equipment. An individualized timetable was prepared to ensure that each participant attended on predetermined days and at specified times. The intervention comprised 30 sessions conducted three times per week, generally on alternate days, with each session lasting approximately 45 minutes. Sessions were held during morning hours under relatively consistent environmental conditions. At the beginning of each session, the child sat comfortably in front of the computer monitor. The cleanliness of the child's hair and scalp was checked to reduce recording impedance and improve signal quality. The distance between the nasion andinion was measured according to the international 10–20 system for electroencephalographic electrode placement. The EEG cap and relevant contact areas were disinfected and carefully positioned on the child's head. Conductive gel was then applied, and the active electrode was placed at the F4 location, corresponding to the right frontal region associated with attentional control, response inhibition, and working-memory processes. The ground electrode was attached to the right earlobe and the reference electrode to the left earlobe. After the signal quality had been checked and artifacts had been minimized, the child completed computer-based

neurofeedback exercises using SmartMind Neurofeedback Software, version 3. This software includes game-like cognitive rehabilitation exercises developed to strengthen cognitive functions while simultaneously providing feedback based on brainwave activity. Its exercises are designed particularly to reinforce working memory, attentional control, concentration, response inhibition, decision-making, problem-solving, and cognitive flexibility. The program provided visual and auditory feedback according to the child's real-time EEG activity, meaning that progress within the computerized game was contingent on producing the targeted pattern of brain activity. The difficulty and duration of the exercises were adjusted according to the standardized settings of the software and the participant's performance. The software also permitted artifact rejection, timing of individual games, application of predefined training protocols, and storage of individual performance data in graphical and numerical formats. Throughout each session, the specialist monitored electrode contact, signal quality, child engagement, and possible fatigue. Brief pauses were provided when needed, while the total training time was kept as consistent as possible across participants.

The sham neurofeedback condition was included to control for expectancy effects, contact with the intervention specialist, exposure to the treatment environment, and the possible psychological influence of believing that an active neurofeedback intervention was being received. Participants in this group attended the same designated neurofeedback room and followed a schedule comparable to that of the active neurofeedback group. They completed 30 sessions, three times per week, with each session lasting approximately 45 minutes. At the beginning of the intervention, the neurofeedback specialist explained the equipment and general session procedure without informing the children that the feedback was noncontingent. Electrode preparation and placement followed the same procedures used in the active neurofeedback group. The child was seated in front of the computer, the nasion-inion distance was determined using the international 10–20 system, and the active, reference, and ground electrodes were attached at the same locations used for the active condition. However, the audiovisual feedback presented during the computerized exercises was not systematically contingent on the child's own moment-to-moment EEG activity. Thus, participants experienced the appearance and structure of a neurofeedback session without receiving a genuine reinforcement protocol based on their individual brainwave patterns. The room

conditions, session duration, frequency of attendance, interaction with the specialist, computer display, and general instructions were kept as similar as possible to those of the active neurofeedback group. This procedure was intended to ensure that differences between the active and sham groups could be attributed more confidently to the specific effects of contingent neurofeedback rather than to attention from the therapist, repeated computer use, motivation, or intervention-related expectations.

The exergaming intervention was conducted in a separate room equipped with a Microsoft Kinect motion-sensing device connected to an Xbox One console and a 49-inch Samsung LED television. Before the intervention began, the children and their parents were invited to an orientation session during which a trained specialist explained the operation of the Kinect system, demonstrated the required movements, and introduced the rules and safety considerations associated with the games. Each participant received an individualized schedule specifying the days and times of attendance. The intervention consisted of 30 sessions conducted three times per week, with each session lasting approximately 45 minutes. The principal intervention was based on the Shape Up exergame, developed by Ubisoft for the Xbox One platform. Shape Up is a movement-based sports and fitness game that uses motion sensors to capture and reproduce the player's body movements on the screen. The game incorporates a broad range of activities, including jumping, running in place, punching, lifting simulated weights, performing push-up-like movements, and completing other dynamic whole-body tasks. These activities require the player to attend continuously to visual instructions, coordinate bodily responses, inhibit irrelevant actions, remember movement sequences, and modify performance according to immediate feedback. The game presents physical exercise in a playful and competitive format and automatically adapts aspects of task difficulty to the player's performance level. Many activities are organized into brief, approximately 90-second exercise sequences, allowing children to complete repeated bouts of cognitively engaging physical activity while reducing monotony and excessive fatigue. During each session, the specialist selected age-appropriate activities, monitored correct movement execution, and ensured that the child maintained a safe distance from the equipment and surrounding objects. The sessions included sufficient time for familiarization, active gameplay, brief recovery intervals, and progression to more demanding exercises when the participant demonstrated adequate mastery. The

same overall session duration and weekly frequency were maintained across participants. The intervention was intended to combine the physiological benefits of movement with the attentional, inhibitory, visuospatial, and information-updating demands of interactive digital games, thereby providing repeated stimulation of cognitive processes involved in working-memory performance.

2.4. Data Analysis

The collected data were analyzed using IBM SPSS Statistics, version 26. Descriptive statistics, including the mean, standard deviation, frequency, and percentage, were used to summarize the participants' demographic characteristics and working-memory scores at the pretest, posttest, and one-month follow-up assessments. Because working memory was measured repeatedly across three assessment occasions and compared among four independent groups, the principal inferential analysis was conducted using a two-factor mixed analysis of variance. In this analysis, time, consisting of the pretest, posttest, and follow-up assessments, was treated as the within-subject factor, while group, consisting of active neurofeedback, sham neurofeedback, exergaming, and control conditions, was treated as the between-subject factor. The main effect of time was examined to determine whether working-memory performance changed across the three assessments, and the main effect of group was evaluated to determine whether the groups differed in their overall performance. Particular attention was given to the time-by-group interaction, because a statistically significant interaction would indicate that the pattern of change over time differed among the four

groups. Before conducting the main analysis, the relevant statistical assumptions were evaluated, including the identification of extreme values, approximate normality of score distributions, homogeneity of variances, and sphericity of repeated measurements. When the assumption of sphericity was violated, an appropriate correction, such as the Greenhouse–Geisser adjustment, was applied. Where significant main or interaction effects were identified, pairwise comparisons with an appropriate adjustment for multiple testing were used to determine which assessment occasions and intervention groups differed significantly. Effect-size indices were also considered to evaluate the magnitude of the observed intervention effects beyond statistical significance. All statistical tests were two-tailed, and the level of statistical significance was set at $p \leq .05$.

3. Findings and Results

Before conducting the inferential analyses, the mean and standard deviation of working-memory scores were calculated for the neurofeedback, sham neurofeedback, exergaming, and control groups across the pretest, posttest, and one-month follow-up assessments. As presented in Table 1, the groups had relatively comparable working-memory scores at pretest. However, the scores increased at posttest and follow-up in both active intervention groups, whereas only minor fluctuations were observed in the sham neurofeedback and control groups. These descriptive findings indicate that both neurofeedback and exergaming were associated with improvements in working-memory performance, and that these improvements were maintained or further increased at the one-month follow-up.

Table 1

Descriptive Statistics for Working-Memory Scores by Group and Assessment Time

Assessment	Neurofeedback Group (n = 14), M	SD	Sham Neurofeedback Group (n = 12), M	SD	Exergaming Group (n = 14), M	SD	Control Group (n = 12), M	SD
Pretest	56.80	11.20	52.50	15.20	48.10	12.30	51.08	19.01
Posttest	66.20	7.20	53.30	11.70	60.30	11.30	46.90	17.40
Follow-up	72.90	8.10	52.90	13.70	68.00	8.60	54.00	

A 4 (group) * 3 (time) ANOVA with repeated measures of last factor was conducted to examine changes in working-memory scores across the pretest, posttest, and follow-up assessments and to determine whether the pattern of change differed among the four study groups. The complete results of the analysis are presented in Table 2.

Table 2
*Results of the 4*3 Mixed ANOVA for Working Memory*

Source	Sum of Squares	df	Mean Square	F	p	Partial η^2
Group	5,091.90	3	1,697.30	3.66	.019	.18
Between-subject error	22,243.30	48	463.40	—	—	—
Time	2,483.50	2	1,241.70	53.04	< .001	.52
Time $\times$ Group	2,116.90	6	352.80	15.07	< .001	.48
Within-subject error	2,247.30	96	23.40	—	—	—

The results of the mixed analysis of variance indicated a statistically significant main effect of time on working-memory scores, $F(2, 96) = 53.04$, $p < .001$, partial $\eta^2 = .52$. This finding indicates that working-memory performance changed significantly across the pretest, posttest, and follow-up assessments, regardless of group membership. The main effect of group was also statistically significant, $F(3, 48) = 3.66$, $p = .019$, partial $\eta^2 = .18$, indicating an overall difference in working-memory performance among the four groups. More importantly, the interaction between time and

group was statistically significant, $F(6, 96) = 15.07$, $p < .001$, partial $\eta^2 = .48$. The large interaction effect demonstrates that the pattern of change in working-memory scores over time differed significantly among the neurofeedback, sham neurofeedback, exergaming, and control groups. Therefore, pairwise comparisons adjusted using the Bonferroni correction with the bootstrap procedure were conducted to identify the immediate effects of each intervention at posttest and the sustained effects at the one-month follow-up (Table 3).

Table 3
Bonferroni-Adjusted Pairwise Comparisons in Working Memory at Posttest and Follow-up

Assessment and Comparison	Mean Difference	p	Bootstrapped BCa 95% CI	Interpretation
Posttest: Immediate Effect				
Neurofeedback vs. sham neurofeedback	14.70	.018	[4.50, 25.60]	Significant
Neurofeedback vs. exergaming	-9.40	.112	[-20.20, 1.30]	Not significant
Neurofeedback vs. control	24.10	.010	[8.40, 42.30]	Significant
Sham neurofeedback vs. control	9.41	.280	[-5.66, 27.60]	Not significant
Exergaming vs. control	33.60	.002	[16.50, 52.20]	Significant
Follow-up: Sustained Effect				
Neurofeedback vs. sham neurofeedback	27.90	.001	[15.05, 40.70]	Significant
Neurofeedback vs. exergaming	-16.80	.077	[-36.70, 0.37]	Not significant
Neurofeedback vs. control	22.10	.004	[10.40, 34.30]	Significant
Sham neurofeedback vs. control	-5.80	.369	[-19.10, 6.60]	Not significant
Exergaming vs. control	38.90	.001	[22.10, 59.90]	Significant

The results of pairwise comparisons indicated that, at posttest, the improvement in working memory was significantly greater in the neurofeedback group than in the sham neurofeedback group, mean difference = 14.70, $p = .018$, BCa 95% CI [4.50, 25.60]. The neurofeedback group also demonstrated a significantly greater improvement than the control group, mean difference = 24.10, $p = .010$, BCa 95% CI [8.40, 42.30]. These findings indicate that neurofeedback produced a significant immediate improvement in the working memory of children with ADHD. However, the difference between the neurofeedback and exergaming groups was not statistically significant, mean difference = -9.40, $p = .112$, BCa 95% CI [-20.20,

1.30], indicating that the immediate effectiveness of the two active interventions did not differ significantly. The comparison between the sham neurofeedback and control groups was also nonsignificant, mean difference = 9.41, $p = .280$, BCa 95% CI [-5.66, 27.60], suggesting that exposure to the intervention setting and noncontingent feedback alone did not significantly improve working memory. In contrast, the exergaming group showed a significantly greater improvement than the control group, mean difference = 33.60, $p = .002$, BCa 95% CI [16.50, 52.20], confirming a significant immediate effect of exergaming on working-memory performance.

At the one-month follow-up, the neurofeedback group continued to show significantly greater improvement than the sham neurofeedback group, mean difference = 27.90, $p = .001$, BCa 95% CI [15.05, 40.70], and the control group, mean difference = 22.10, $p = .004$, BCa 95% CI [10.40, 34.30]. These results demonstrate that the beneficial effect of neurofeedback on working memory was maintained one month after the intervention. The exergaming group also showed a significantly greater sustained improvement than the control group, mean difference = 38.90, $p = .001$, BCa 95% CI [22.10, 59.90], indicating that the effects of exergaming remained significant at follow-up. No statistically significant difference was found between the neurofeedback and exergaming groups at follow-up, mean difference = -16.80, $p = .077$, BCa 95% CI [-36.70, 0.37]. Thus, neither active intervention was statistically superior to the other in producing sustained improvements in working memory. Moreover, the difference between the sham neurofeedback and control groups remained nonsignificant, mean difference = -5.80, $p = .369$, BCa 95% CI [-19.10, 6.60], further indicating that sham neurofeedback did not produce a meaningful immediate or sustained improvement. Overall, the findings supported the effectiveness of both neurofeedback and exergaming in improving the working memory of children with ADHD, with the effects of both interventions remaining evident one month after treatment.

4. Discussion

The present study examined the effects of neurofeedback and exergaming on working memory in children with attention-deficit/hyperactivity disorder using a randomized pretest, posttest, and one-month follow-up design that included active neurofeedback, sham neurofeedback, exergaming, and control groups. The results demonstrated significant main effects of time and group, as well as a significant interaction between time and group. These findings indicate that working-memory performance changed across the three measurements and that the pattern and magnitude of change differed among the four groups. More specifically, children who received active neurofeedback showed significantly greater improvement than those in the sham neurofeedback and control groups at both posttest and follow-up. Children who participated in the exergaming intervention also showed significantly greater gains than the control group at both tests. In contrast, sham neurofeedback did not produce a significant advantage over the control group. No statistically significant difference was

found between neurofeedback and exergaming at either posttest or follow-up. Overall, the findings suggest that both active interventions produced immediate and sustained improvements in working memory, whereas exposure to the treatment setting and noncontingent feedback alone was insufficient to create comparable changes.

The significant improvement observed following neurofeedback is consistent with evidence indicating that this intervention can strengthen executive functions in children with ADHD. A recent systematic review and meta-analysis found that neurofeedback training can improve executive-function outcomes in children with ADHD, although the magnitude of the effect may differ according to the protocol and executive functions assessed (Zhong et al., 2025). Earlier meta-analytic findings from randomized controlled trials also indicated that neurofeedback may improve clinical symptoms and selected neuropsychological outcomes in children with ADHD (Cortese et al., 2016). The present findings extend this literature by showing that working-memory gains were not limited to the immediate post-intervention assessment but remained evident one month after completion of training. This maintenance effect is clinically relevant because an intervention that produces only short-lived task improvement would have limited rehabilitative value.

The findings also align with previous research specifically addressing working memory. Neurofeedback training has been shown to improve sustained attention and working memory in primary-school boys with ADHD (Dasht Bozorgi et al., 2016). Similarly, the combination of neurofeedback and computerized cognitive exercises has been associated with improved working-memory performance, supporting the idea that repeated feedback-guided practice may strengthen the cognitive processes involved in maintaining, updating, and manipulating information (Heidari Nasab et al., 2016). Review studies have likewise concluded that neurofeedback can be useful in the treatment of ADHD, particularly when the intervention is delivered through structured and sufficiently intensive protocols (Nemati & Alizadeh, 2017). Evidence of reduced inattention and hyperactivity following neurofeedback among school-aged students and young adults further supports the broader regulatory effects of this intervention (Narimani et al., 2013; Seilsapour et al., 2015).

One possible explanation for the neurofeedback findings is that repeated contingent feedback enabled participants to develop greater control over neural activity associated with attention, response regulation, and executive control.

Neurofeedback is based on operant learning principles: desirable electrophysiological patterns are reinforced through immediate visual or auditory consequences, gradually increasing the individual's ability to reproduce those patterns. The theoretical and clinical foundations of neurofeedback suggest that repeated self-regulation of brain activity may modify the functional systems underlying attention and cognitive control (Heinrich et al., 2016; Sterman & Egner, 2006). In the present study, the active electrode was placed over the right frontal region, which is relevant to attentional regulation, inhibitory control, and working-memory processing. Repeated activation and regulation of this area may therefore have helped children maintain task-relevant information, resist distraction, and update responses more effectively.

The use of game-like computerized exercises during neurofeedback may also have contributed to the observed improvement. Children with ADHD often have difficulty persisting in monotonous or delayed-reward tasks. Immediate feedback, visible progress, and repeated opportunities for success can increase motivation and sustain engagement. The SmartMind exercises used in this study required participants to coordinate cognitive performance with ongoing brain-based feedback, thereby integrating neural self-regulation with practice in attention, inhibition, and working memory. Findings from computerized working-memory interventions indicate that repeated and adaptive training can improve working memory and attention, particularly when the trainings are structured according to the participant's performance level (Gray et al., 2012). The combination of feedback, repetition, and cognitive challenge may consequently explain why the active neurofeedback group improved more than the sham group.

The absence of a significant difference between sham neurofeedback and the control group is an important finding. It suggests that the improvements associated with active neurofeedback were unlikely to be explained solely by contact with the specialist, sitting in front of a computer, wearing EEG equipment, receiving treatment-related attention, or expecting improvement. Concerns about the specificity of neurofeedback have been raised in the literature because participants may benefit from nonspecific therapeutic factors, repeated assessment, or motivational engagement rather than from modulation of targeted brain activity (Brandeis, 2011). By including a sham condition in which feedback was not contingent on the participant's actual EEG pattern, the present study provided a stricter test

of treatment specificity. The significant superiority of active neurofeedback over sham neurofeedback at both posttest and follow-up therefore supports the interpretation that contingent neurophysiological feedback contributed meaningfully to the observed working-memory gains.

Nevertheless, the neurofeedback literature has not produced entirely uniform conclusions. Reviews have described neurofeedback as promising while also emphasizing variability in training protocols, blinding, outcome measures, and control conditions (Holtmann et al., 2014). A randomized trial comparing neurofeedback, stimulant medication, and physical activity found that treatment effects varied across neurocognitive outcomes and that neurofeedback was not consistently superior on every measure (Gelade et al., 2016). Such variation may reflect differences in electrode placement, reinforcement thresholds, number of sessions, participant characteristics, concurrent treatment, and the cognitive domain being evaluated. The current study's relatively intensive 30-session protocol may have provided sufficient repetition for children to acquire and consolidate self-regulatory skills, which may partly account for the sustained improvement.

The positive effect of exergaming on working memory is also consistent with previous research. A randomized controlled trial reported that exergaming improved attention in children with ADHD, demonstrating that cognitively engaging physical games can influence functions beyond movement performance (Ji et al., 2023). Movement-based computerized cognitive rehabilitation has similarly been found to improve working memory in children with ADHD (Jalili et al., 2019). In addition, sport-game training has been associated with enhanced self-control and regulation in this population (Salleg-Cabarcas et al., 2024). The present results add to this evidence by showing that the benefits of exergaming extended specifically to working memory and were maintained at the one-month follow-up assessment.

Several mechanisms may explain the effectiveness of exergaming. First, physical activity may facilitate cognitive performance by increasing physiological arousal, cerebral circulation, and activation of neural networks involved in executive control. Second, exergames require simultaneous perceptual, cognitive, and motor processing. During Shape Up activities, children had to observe rapidly changing visual cues, retain game rules, anticipate upcoming actions, select appropriate movements, inhibit incorrect responses, and modify performance in response to immediate feedback. These demands closely involve working memory because the child must continuously hold and update task-relevant

information while performing physical actions. The combination of exercise and cognitive challenge may therefore generate stronger executive engagement than either passive gaming or repetitive physical exercise alone.

The motivational properties of exergaming may offer an additional explanation. Interactive games provide immediate rewards, clear goals, performance feedback, progressive difficulty, and frequent changes in stimulation. These features can be especially useful for children with ADHD, who may show reduced persistence when tasks are repetitive or rewards are delayed. Video game research has demonstrated that game playing can engage attention, memory, and executive control, although the transfer of benefits depends on the cognitive requirements of the game (Boot et al., 2008). The role of anticipation and expectation in maintaining attention may also be relevant, because game events create continuous cycles of prediction, action, and feedback (Huron, 2007). In the present study, short movement challenges and adaptive game difficulty may have sustained children's engagement across 30 sessions and enabled repeated practice of working-memory-related skills without the intervention being experienced as a conventional cognitive exercise.

The exergaming findings may also be understood in relation to evidence that Kinect-based interventions support motor learning through repeated, visually guided practice. Computerized motor training using Xbox Kinect has been shown to improve gross motor skills among children with motor delays (Rostamipour et al., 2019). Although the outcome in the present study was cognitive rather than motor, movement coordination and executive control are not independent. Planning a movement, monitoring its execution, correcting errors, and shifting between action patterns require cognitive control. The motor and cognitive components of exergaming may therefore reinforce one another, resulting in improvements in working memory.

The significant difference between the exergaming and control groups at both posttest and follow-up further indicates that the observed gains were unlikely to reflect only repeated exposure to the N-Back task or developmental change. Children in the control group did not show a comparable pattern of improvement. This finding is compatible with research showing that technology-assisted cognitive rehabilitation and structured computer games can improve executive and behavioral outcomes in children with ADHD (Nazerieh & Niknam, 2024; Nejati & Derakhshan, 2024). However, the findings should not be interpreted as evidence that unrestricted video game use is beneficial.

Problematic and excessive gaming has been associated with ADHD, anxiety, and depression among children and adolescents (Alrahili et al., 2023). Therapeutic exergaming differs from uncontrolled gaming because it is supervised, time-limited, developmentally appropriate, physically active, and organized around specific cognitive and rehabilitative objectives.

The absence of significant differences between neurofeedback and exergaming at posttest and follow-up suggests that neither intervention was clearly superior in improving working memory. This finding may indicate that different intervention mechanisms can lead to a similar functional outcome. Neurofeedback may act primarily through learned regulation of neural activity, whereas exergaming may influence working memory through physical activity, cognitive-motor integration, motivation, and repeated practice on executive functions. Both interventions provide immediate feedback and require sustained, goal-directed engagement. These common characteristics may be more important for working-memory improvement than the specific delivery modality. The finding also supports a flexible treatment perspective in which intervention selection can be based on child characteristics, available resources, treatment preferences, cost, and feasibility rather than an assumption that one approach is universally superior.

The comparable effectiveness of the two interventions is consistent with broader evidence that executive functions can be enhanced through multiple forms of targeted training. Recent reviews of neurofeedback in neurological and psychiatric settings emphasize that feedback-guided learning can support self-regulation across diverse conditions (Melo et al., 2025). Neurofeedback has also shown effects across different protocols and functional domains, including anxiety regulation, mindfulness-related self-regulation, and performance enhancement (Lotfinia et al., 2025; Treves et al., 2025; Yu et al., 2025). Similarly, game-based cognitive and physical interventions can stimulate executive functions through adaptive challenge and active engagement. The present results suggest that both pathways may be clinically useful for children with ADHD when implemented systematically and intensively.

The sustained effects observed at follow-up may reflect consolidation of learned skills. In neurofeedback, repeated practice may have enabled children to internalize strategies for regulating attention and neural activation even after the external feedback was removed. In exergaming, repeated requirements to remember instructions, shift between tasks,

inhibit impulsive actions, and coordinate complex movements may have strengthened executive processes that remained available after training ended. The continued improvement in posttest scores to follow-up in both active groups may also indicate that children applied acquired skills in everyday academic and behavioral contexts. Nevertheless, because the study assessed follow-up after only one month, the duration of these effects beyond the short term remains uncertain.

The current findings are also relevant to the increasing demand for nonpharmacological and child-friendly ADHD interventions. Pharmacological treatments remain central to evidence-based ADHD management and can produce substantial symptom reduction (Bolea-Alamanac et al., 2014). However, medication does not directly provide repeated practice in working-memory tasks, and some families prefer nonpharmacological or complementary options. Comparative research has shown that both medication and neurofeedback may produce beneficial outcomes, although they differ in their delivery and mechanisms (Mohammadi & Hosseini, 2018). The current results do not suggest replacing established medical treatment with either intervention. Rather, neurofeedback and exergaming may serve as complementary approaches for children whose treatment plans require additional support for executive functions.

This study had several limitations. First, the sample consisted only 52 boys aged 7-10 years from mainstream primary schools in one geographical area, which restricts the generalizability of the findings to girls, adolescents, children from other regions, and those with different clinical or socioeconomic characteristics. Second, the relatively small sample sizes within the four groups may also have reduced statistical power for detecting modest differences, particularly between the two active interventions. Third, working memory was assessed using a single computerized task, and repeated administration may have produced practice effects. Fourth, although the sham group strengthened the research design, complete blinding of intervention providers was not feasible. Fifth, we did not systematically control for medication use, ADHD subtype, symptom severity, sleep quality, physical activity outside sessions, or concurrent treatments that could influence cognitive performance. Finally, the one-month follow-up was relatively short and does not establish whether the observed benefits persist over longer periods or generalize to academic performance, classroom behavior, and everyday functioning.

Future studies should recruit larger, more diverse samples that include girls, different age ranges, and participants from various educational and cultural settings, as well as those with varying ADHD presentations and symptom severity. Longer follow-up periods (e.g., 3, 6, and 12 months) would clarify the durability of treatment effects. Researchers are encouraged to use several measures of working memory and executive functions, together with parent, teacher, and behavioral assessments, to evaluate transfer effects beyond laboratory tasks. Systematic documentation of medication status, comorbid conditions, attendance, treatment fidelity, and participant engagement is essential. Direct comparisons of different neurofeedback protocols and different types or intensities of exergaming would help identify the most effective intervention components. Studies could also examine mediating mechanisms, such as improvements in inhibitory control, sustained attention, physical fitness, motivation, or neural regulation. Moreover, factorial designs comparing neurofeedback, exergaming, and a combined intervention may determine whether integrating the two approaches produces additive or synergistic benefits.

5. Conclusion

This randomized controlled trial demonstrated that both active neurofeedback and supervised exergaming produced significant and sustained improvements in working memory among children with ADHD, as measured by the N-Back task. At posttest and one-month follow-up, each active intervention outperformed the sham and control groups. However, no statistically significant difference was found between the two active interventions at either assessment, indicating that neither intervention was clearly superior. These findings suggest that technology-based, non-pharmacological interventions—whether centered on neural self-regulation or on cognitively engaging physical activity—can serve as effective complementary tools for strengthening working memory in this population. Nevertheless, given the limited sample diversity, short follow-up period, and reliance on a single laboratory task, the results should be interpreted cautiously. Future research with larger, more representative samples and longer follow-ups is needed to confirm the durability and ecological validity of these gains. For clinical practice, intervention selection may be guided by individual child characteristics, resources, and preferences, rather than by assuming the overall superiority of one method over the other.

Authors' Contributions

Authors equally contributed to this article.

Declaration

In order to correct and improve the academic writing of our paper, the editorial office of this journal has used the language model ChatGPT during the production process.

Transparency Statement

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

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

Ethical approval for this study was obtained from the Research Ethics Committee of Alzahra University (Approval No. [IR.ALZAHRA.REC.1400.057]).

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