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Research Paper

The Combined Effect of Active Video Games and tDCS on Balance and Cognitive Flexibility in Children With ASD

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ABSTRACT

Introduction: This study looked at the effects of combined transcranial direct current stimulation (tDCS) and exergaming therapy on the balance and cognitive flexibility in children with autism spectrum disorder (ASD).

Methods: A quasi-experimental randomized controlled trial (RCTs) study was undertaken with 30 children aged 7-10 years, who were randomly allocated to either an experimental group (n=15) getting active tDCS (1.5 mA over the left DLPFC) + Kinect-based exergaming or a control group (n=15) receiving sham tDCS with exergaming. The 4-week intervention (3 sessions per week) was preceded and followed by extensive evaluations using the movement assessment battery for children-2 (MABC-2) and the Wisconsin card sorting test (WCST).

Results: Analysis of covariance (ANCOVA) showed significant between-group differences favoring the experimental group for static balance ($F=9.537$, $P<0.001$, $\eta_p^2=0.128$) and dynamic balance ($F=7.51$, $P<0.001$, $\eta_p^2=0.158$), with medium-to-large effect sizes. The results showed that the combined tDCS and exergame intervention had a stronger effect on improving cognitive flexibility than exergame alone. This improvement was associated with a significant increase in correct and conceptual responses and a decrease in repetitive errors in the combined group ($P<0.001$).

Conclusion: The work fills a key gap in neurorehabilitation research by presenting empirical data for combined neuromodulation and digital-motor therapies in ASD. The findings encourage the creation of tailored protocols that target both cognitive and motor networks concurrently. Future studies should look at long-term maintenance effects and the brain processes that underpin these synergistic advantages. This integrated strategy holds promises for improving motor learning and functional results in children with neurodevelopmental problems.

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Highlights

- The research aimed to investigate the synergistic effects of combining tDCS with exergaming on cognitive postural balance in children with ASD. A randomized controlled design was employed, involving thirty ASD participants aged 7–10 years, divided into an active tDCS + exergaming group and a sham tDCS + exergaming control group over a four-week intervention.

- Children receiving active tDCS alongside exergaming demonstrated a significant improvement in cognitive flexibility compared with the sham group, as measured by standardized executive-function tasks.

- The active stimulation group showed greater postural stability and enhanced dynamic balance after the intervention, indicating that neural modulation may facilitate better motor control and integration.

- The concurrent application of tDCS and exergaming likely created a neuroplastic synergy, enhancing cortical excitability and adaptive brain reorganization related to both motor and cognitive domains.

- The dual-modal intervention appears to be a promising non-pharmacological approach for neurorehabilitation in children with ASD, integrating cognitive training and sensorimotor engagement to target underlying executive and motor deficits.

Plain Language Summary

This study explored whether combining transcranial direct current stimulation (tDCS), a gentle electrical stimulation applied to the brain, with active video gaming (exergaming) could improve motor balance and cognitive flexibility in children diagnosed with autism spectrum disorder (ASD). Thirty children aged seven to ten participated and were divided into two groups. One group received real brain stimulation (active tDCS) along with exergaming, while the other group received sham stimulation but played the same games. The intervention lasted four weeks, with three sessions per week. Before and after the treatment, the researchers assessed the children's balance and cognitive skills. Results showed that those who received the combined treatment demonstrated significantly greater improvement in cognitive flexibility, meaning they could shift their thinking more easily, make more accurate decisions, and repeat fewer errors. The findings suggest that this combined approach of brain stimulation and interactive physical gaming may be an effective way to enhance both mental and motor abilities in children with ASD, offering new possibilities for integrated brain–body rehabilitation.

Introduction

Autism spectrum disorder (ASD) is a complicated neurodevelopmental disease defined by chronic difficulties in social communication and interaction, as well as confined, repetitive patterns of behavior or interests (American Psychiatric Association, 2022; Qeysari et al., 2017). Epidemiological statistics show a large gender discrepancy, with males diagnosed 4 times more commonly than females (Loomes et al., 2017). The most recent CDC (Centers for Disease Control and Prevention) surveillance statistics show a prevalence rate of 1 in 36(2.8%) among 8-year-old children in the United States (Maenner et al., 2023).

Individuals with ASD typically demonstrate motor impairments, such as postural instability (Weimer et al., 2021), gait irregularities (Kindregan et al., 2015), and poor fine motor coordination (Bhat, 2021). According to neurodevelopmental research, 79-87% of children with ASD experience clinically severe motor coordination impairments (Bhat et al., 2022). Furthermore, new research identifies key executive function deficiencies in planning, cognitive flexibility, and attentional control (Chen et al., 2016; Demetriou et al., 2019; Christakou et al., 2013), even among individuals without intellectual disabilities. Current diagnostic techniques prioritize behavioral observation with standardized instruments such as the ADOS-2 (Lord et al., 2020) and diagnostic and statistical manual of mental disorders (DSM-5-TR) criteria (American Psychiatric Association, 2022).

In recent years, there has been an increasing interest in noninvasive intervention techniques, including structured physical exercise and active video games (exergames), as viable alternative tactics to established therapy for children with ASD. According to recent research, these digital-motor hybrid technologies create engaging, low-stress environments that not only increase motivation and participation in physical activity (Fang et al., 2019), but also induce measurable cognitive improvements via neuroplasticity mechanisms. These benefits include increased cognitive flexibility, selective attention, and information processing speed (Zhu et al., 2021; Tarr et al., 2022). Neuroimaging data show that these cognitive advantages are associated with structural and functional alterations in brain networks, including greater functional connectivity in frontoparietal attention networks and improved white matter integrity (Tsermentseli et al., 2022). Longitudinal studies show that regular exergame use can significantly reduce repetitive behaviors, possibly via emotional control processes and modulation of the dopaminergic system (Zhao et al., 2023).

Noninvasive brain stimulation (NIBS) has emerged as a possible treatment for children with ASD, with increasing data supporting its ability to modify aberrant neural pathways. Recent research has shown that techniques, such as repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS) can improve cognitive functioning and reduce repetitive behaviors by targeting key neural networks, such as the dorsolateral prefrontal cortex (dlPFC) and cerebellar-thalamo-cortical pathways (Wang et al., 2023). A systematic meta-analysis of 22 randomized controlled trials (RCTs) involving 829 children with ASD found that NIBS interventions resulted in significant reductions in repetitive behavior scores (SMD=-0.68; 95% CI: -0.82%, -0.54%) as well as improvements in executive functions (SMD=0.59; 95% CI, 0.42%, 0.76%) (Liu et al., 2023a).

Emerging research suggests that tDCS may improve motor skills and balance in children with ASD by modulating corticocerebellar circuits. Recent RCTs show that anodal stimulation (1-2 mA) over the primary motor cortex (M1) or cerebellar region (lobules VII-IX) improves fine motor precision (9-12% reduction in Purdue Pegboard completion time, $P<0.05$), dynamic balance (20-25% reduction in postural sway during eyes-closed conditions), and gait coordination (15-18% increase in stride length variability) (Zhao et al., 2023; Pereira et al., 2024). These behavioral gains are associated with neurophysiological changes, such as increased motor cortical excitability (30-35% increase in motor-evoked potentials), improved functional connectivity between cerebellar dentate nuclei and contralateral M1 (functional magnetic resonance imaging [fMRI] resting-state functional connectivity [rs-FC] r=0.42-0.48), and normalization of sensorimotor mu-rhythm (8-13 Hz) power in resting electroencephalography (EEG) ($P<0.01$).

Despite expanding data on the individual benefits of NIBS and computer-based therapies, no study has looked into the synergistic potential of combining these techniques to improve neuro-motor functioning in children with ASD. This study fills a key knowledge gap by determining whether a combination protocol of tDCS and active video gaming can expedite gains in (a) dynamic balance and (b) cognitive flexibility when compared to single-modality therapies. Based on modern neuroscience principles, the study combines cutting-edge results on stimulation-induced neuroplasticity with game-based motor learning to provide a unique theoretical framework for integrated therapies in neurodevelopmental disorders. The findings may provide empirical evidence for the development of tailored neuromodulation protocols that concurrently address cognitive and motor brain networks, leading to more successful ASD therapy techniques.

Materials and Methods

Research type

This quasi-experimental RCT study employed a pre-test-post-test design with a control group. It included 30 children aged 7 to 10 years with ASD, clinically diagnosed by a child psychiatrist using DSM-5 criteria. Participants were first matched in pairs based on age, gender, and ASD severity. Each matched pair was then randomly assigned, by block randomization, to either the experimental group or the control group (n=15 per group).

Study participants

The study participants met the following inclusion criteria: (1) a confirmed diagnosis of ASD level 1 according to DSM-5 criteria, (2) a chronological age of 7–10 years, (3) the ability to follow simple motor instructions, (4) no current use of psychiatric medication, (5) no history of seizure disorders or epilepsy, and (6) provision of informed parental consent. The exclusion criteria were as follows: (1) missing more than two intervention sessions, (2) experiencing adverse effects (e.g. severe headache or agitation), and (3) failure to comply with the protocol.

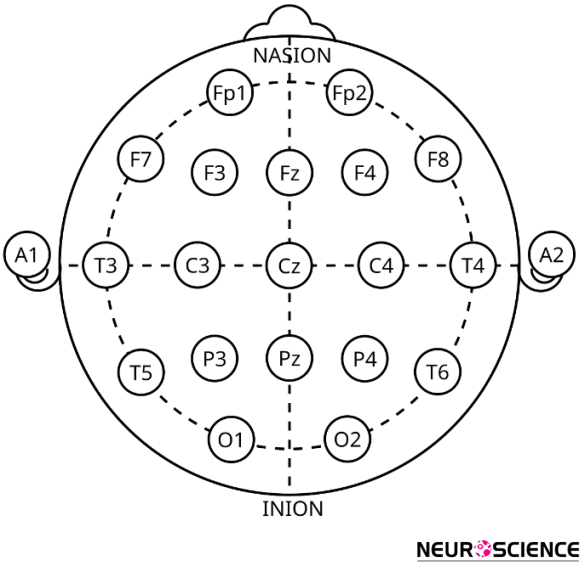

Figure 1. Schematic illustration of the international 10–20 eeg electrode placement system

Study material

tDCS device

The study used a tDCS device (Active DOSS-2) delivering a constant 1.5 mA. The stimulation protocol consisted of six 20-min sessions over 4 weeks, using saline-soaked sponge electrodes (25 cm^2) positioned according to the international 10–20 EEG system. The anode was placed over the left dlPFC (F3) and the cathode over the right supraorbital region (Figure 1). In the sham condition, the device applied a standard 30-s ramp-up and fade-out procedure, after which stimulation was discontinued to mimic the initial sensations of real stimulation. To ensure blinding, participants, parents/caregivers, and outcome assessors were blinded to group allocation, and the device screen was concealed during both active and sham sessions. Only the researcher who programmed the device and maintained the randomization list was aware of allocation; all other study personnel remained blinded. All stimulation parameters were selected in accordance with internationally accepted tDCS guidelines and previous evidence-based protocols.

The Xbox One gaming system

The Xbox One was designed as a computer game console comparable to PlayStation systems. It outperforms PlayStation models in terms of build quality and performance. The inclusion of Kinect technology adds a novel feature that lets players control games solely through body motion. Kinect, in particular, uses a sophisticated optical lens and motion sensors to detect a user's limb motions within a set range of the device and transmits this information to the system in real time. These movements are translated into the user's digital avatar in the game world, creating a dynamic, seamless interactive experience.

This technology has several major advantages, including greater physical activity, improved motor coordination, and the possibility for instructional gaming applications, all of which contribute favorably to users' physical and psychological well-being. These properties are particularly useful in rehabilitative treatment and interactive training applications (Hondori et al., 2014).

Kinect motion sensor

This clever motion- and audio-detection technology makes monitoring easier without requiring specific clothing or equipment. Kinect's excellent sensors enable it to perform accurately across a wide range of lighting conditions, from low to high. Furthermore, the technique delivers extensive three-dimensional data on body joint positions, making it useful for movement analysis (Gao et al., 2015). Microsoft uses RGB-D camera technology to acquire accurate motion data, allowing for full three-dimensional body tracking. This high-precision technology finds applications in a variety of sectors, including medicine, sports science, and video games (Cai et al., 2017).

Rivals sports installation software

Rivals is Xbox One-specific software. This program offers a variety of sporting activities, including bowling, kayaking, rock climbing, soccer, clay tennis, and shooting. We chose clay tennis as our major study game. The program is designed to provide a realistic and entertaining sports experience, leveraging innovative motion-sensing technologies to enhance user engagement. Its advanced motion-tracking capabilities make it a desirable platform for lovers of simulated sports.

The movement assessment battery for children (MABC-2)

The MABC-2 was used in this study to evaluate participants' balance. This standardized exam was particularly useful for assessing static and dynamic balance due to its well-validated balance subscale. MABC-2 is one of the most often used evaluation instruments in occupational therapy, physiotherapy, psychology, and education. This battery is an updated version of the original mobility evaluation for children, created in 1992 for children aged

3 to 16 years. The age range is separated into 3 categories: 3-6, 7-10, and 11-16 years.

The primary components measure manual dexterity, balance, and ball abilities. The rating method has three zones: red (≤5th percentile) for major movement issues, yellow (6th-15th percentile) for borderline performance, and green (≥16th percentile) for normal motor development. This examination provides accurate and useful data for detecting and categorizing children's motor abilities, enabling professionals to plan appropriate therapeutic and educational interventions. Furthermore, the MABC-2 is very useful for diagnosing mobility issues in children with learning impairments or developmental delays, as well as tracking improvement during therapy (Henderson et al., 2007). Ghayour et al. (2022) established the MABC-2's psychometric properties, demonstrating strong reliability (Cronbach α=81-90%) and validity in children with movement impairments.

The Wisconsin card sorting test (WCST)

The WCST is a well-known neuropsychological diagnostic instrument that evaluates key aspects of executive functioning, including cognitive flexibility, abstract reasoning, and problem-solving. This standardized exam shows participants 64 cards that change in three dimensions (color, shape, and number). It requires them to infer the proper sorting principle through trial-and-error feedback before adapting to shifting categorization criteria. Primary outcome measures include completed categories, perseverative mistakes (indicating difficulties shifting mental sets), non-perseverative errors, and conceptual learning efficiency, which together give a full picture of executive function skills.

Computerized versions of the WCST preserve the test's strong psychometric features while improving measurement precision through automated response recording and timing accuracy. Extensive validation studies have established the test's sensitivity and discriminant validity across diverse groups, making it an essential tool for both clinical neuropsychological examinations and cognitive neuroscience research (Heaton et al., 1993).

Gilliam autism rating scale - third edition (GARS-3)

The GARS-3 is a screening tool used to help identify signs and the severity of ASD in people aged 3 to 22. Developed by James E. Gilliam in 2014, this third edition includes updated scoring standards and more detailed subscales to improve accuracy. It contains 56 questions, each rated on a scale from 0 to 3. The GARS-3 looks at 6 key areas: repetitive and restricted behaviors, social communication, social interaction, thinking style, unusual speech patterns, and emotional responses. Research by Gilliam (2014) showed that these areas have good reliability and accuracy in identifying people with autism

Study procedure

The study used a quasi-experimental RCT design with 2 parallel groups. Initially, ethical approval was obtained from the Ethics Committee of the Tehran University. Subsequently, an introductory letter from the Faculty of Physical Education and Sport Sciences of the University of Tehran was submitted to the Tehran Welfare Organization and the Tehran Autism Association to obtain sampling permits. The association provided information on all volunteers willing to participate in the study.

Informed written consent was obtained from each participant's parent or legal guardian, and verbal assent was obtained from the children. Participation was voluntary, and families were informed that they could withdraw at any time without consequences for access to services. All personal identifiers were removed, and each participant was assigned a numeric code. Data files were stored in a password-protected directory accessible only to the principal investigator, and no identifying information was used in any statistical analysis or reporting.

Based on the inclusion criteria, 30 adolescents (25 boys and 5 girls) with high-functioning ASD (ASD level 1), according to their medical records, were selected through convenience sampling. All participants in this study were diagnosed with high-functioning ASD based on the diagnostic criteria outlined in the diagnostic and statistical manual of mental disorders. Participants were randomly assigned to either an experimental group (n=XX) or a control group (n=XX), both of which received motion-based video game treatments via the Kinect system. The experimental group also received anodal tDCS at 1.5 mA for 20 minutes over the left dlPFC. The neurostimulation methodology involved placing the anode electrode in the F3 region and the cathode electrode in the right supraorbital area, according to the international 10-20 system. In the control group, the tDCS device was automatically turned off after 30 seconds to simulate a sham condition.

Each intervention session lasted 40 minutes, beginning with 20 minutes of brain stimulation (active or sham) and ending with 20 minutes of personalized video game training. The intervention was given three times each week for 4 weeks straight (Table 1). The chosen video

Table 1. Active computer game training protocol

1st and 2nd sessions	For children with autism spectrum disorder, it is important to be familiar with the computer program, to play with the gadget, and to wind up.	3rd and 4th sessions	Playing the 1st and 2nd sessions, then commencing the 2nd portion of the clay tennis program.
5th and 6th sessions	Playing the third and fourth sessions before moving on to the third stage of the clay tennis program, which is more challenging than the previous level and requires a deeper understanding of the previous stages.	7th and 8th sessions	Playing the 5th and 6th sessions before moving on to the fourth stage of the clay tennis program, which is more challenging than the previous level and requires more prior knowledge.
9th session and 10th sessions	From sessions 8 and 9, you will proceed to stage 5 of the clay tennis program, which is more challenging than the previous level. If you have mastered the previous stages, the level of play varies depending on the quantity of play, progress, and individual differences.	11th and 12th sessions	This phase involves conducting a standardized virtual match that rigorously applies official tennis regulations. The session will implement the authentic scoring system, enforce mandatory court-side changes after odd-numbered games, and adhere to realistic match timing intervals. This structured approach is designed to enhance cognitive flexibility, adherence to rules, and situational adaptation within an engaging digital environment. The simulation aims to translate acquired gaming skills into structured cognitive-behavioral outcomes.

NEUROSCIENCE

games were specially intended to address both cognitive and motor components. Cognitive and motor tests were administered at baseline and post-intervention. Data analysis was conducted using appropriate statistical techniques to investigate potential interactions between the therapies. This protocol was created to study the potential synergistic benefits of combining NIBS and cognitive-motor training.

Statistical analysis of data

The Shapiro-Wilk test was used to assess normality, and Levene's test to assess homogeneity of variances. After establishing the essential assumptions, an analysis of covariance (ANCOVA) was used to examine within- and between-group changes, with pre-test scores as covariates. To assess differences within groups, paired samples t-tests were used. Statistical analyses were conducted using SPSS software, version 25, with a significance threshold of α=0.05. A post hoc power analysis based on the observed effect sizes showed that statistical power exceeded 0.80 for the main ANCOVA outcomes, indicating adequate sensitivity of the tests despite the modest sample size.

Results

Descriptive data

The Table 2 presents the baseline characteristics of individuals in the control and experimental groups, presented as Mean±SD. The age distribution was similar across groups (control: 7.85±0.67 years; Experimental: 7.75±0.71 years), as were anthropometric Measurements, including weight (control: 25.10±2.42 kg; experimental: 24.72±3.82 kg) and height (control: 124.65±2.08 cm; experimental: 125.85±2.53 cm). In addition, there was no significant difference in autism severity scores between the two groups.

Evaluated data

Balance

After adjusting for baseline (pre-test) scores, ANCOVA indicated statistically significant differences between the experimental and control groups in both static and dynamic balance. Static balance showed a significant main-group effect ($F=9.537$, $P<0.001$, $\eta_p^2=0.128$), with the experimental group outperforming the control group. Similarly, dynamic balance also demonstrated a significant between-group difference ($F=7.51$, $P<0.001$, $\eta_p^2=0.158$), with the experimental group showing better performance.

The effect sizes indicate that the intervention accounts for approximately 12.8% of the variance in static balance and 15.8% in dynamic balance. These results show that the combined tDCS and exergaming protocol had a meaningful positive effect on both balance outcomes, with a slightly greater effect in dynamic balance (Table 3).

Table 2. Descriptive statistics of subjects

Group	Number	Mean±SD			
		Age (y)	Height (cm)	Weight (kg)	Autism Severity (Gars-3)
Experimental	15	7.97±0.81	128.85±3.53	25.65±4.92	56.15±3.94
Sham	15	7.71±0.97	127.65±3.08	25.37±4.42	57.39±4.11

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Cognitive flexibility

The covariance analysis (controlling for pre-test scores) revealed that the combination intervention of TDCS and exergame had a stronger impact on enhancing cognitive flexibility than exergame alone. In the TDCS+exergame group, the mean correct answer rose from 19.17 to 29.05, whereas no significant change was found in the exergame group (F=6.54, P=0.016, η_p^2=0.195). Similarly, conceptual answers in the combined group increased significantly from 0.37 to 2.13, whereas the exergame group showed a more restricted increase (F=7.221, P=0.012, η_p^2=0.211). Furthermore, perseverative mistakes fell from 21.12 to 19.30 in the TDCS+exergame group, while only a modest reduction was detected in the exergame group (F=12.941, P=0.001, η_p^2=0.324). The combination intervention significantly improved cognitive performance compared to exergame alone (P<0.05) (Table 4).

Discussion

The current study examined the effects of combining tDCS with exergaming on balance and cognitive flexibility in children with ASD. Results showed substantial improvements in both static and dynamic balance, as well as enhanced executive function, particularly cognitive flexibility, in the group receiving active tDCS paired with Kinect-based exergaming. These findings suggest that combining neuromodulation with digital motor training may provide distinct benefits over single-modality therapies in children with ASD.

Table 3. Covariance analysis in static and dynamic balance variables

Variables	Mean±SD				F Coefficient	P	Effect size (η^2)
	Experimental		Control				
	Pre-test	Post-test	Pre-test	Post-test			
Static balance	2.31±1.8	3.6±1.8	2.7±1.35	1.7±0.8	9.537	<0.001*	0.128
Dynamic balance	1.79±0.7	2.44±1.6	0.86±0.5	0.98±0.9	7.51	<0.001*	0.158

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Table 4. Covariance analysis on cognitive flexibility variable

Variables	Mean±SD				F Coefficient	P	Effect size (η^2)
	Experimental		Control				
	Pre-test	Post-test	Pre-test	Post-test			
Correct response	19.17±6.6	29.05±7.91	18.9±6.01	18.89±6.8	6.54	0.016	0.195
Conceptual responses	0.37±0.29	2.13±1.19	1.49±0.49	1.97±0.99	7.221	0.012	0.211
Perseverative Errors	21.12±7.89	19.3±8.18	21.47±8.09	20.99±6.989	12.941	0.001	0.324

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The most notable improvement was observed in dynamic balance, consistent with prior research highlighting the role of corticocerebellar circuits in postural control and motor adaptation (Pereira et al., 2024; Wang et al., 2023). Anodal stimulation of the left dlPFC may have enhanced top-down control of cerebellar-thalamic pathways, facilitating motor learning during exergaming (Liu et al., 2023b). Dynamic balance requires continuous integration of multisensory input and rapid motor adjustments, which may explain the superior effect of the combined intervention in this domain (Weimer et al., 2021; Bhat et al., 2022).

Cognitive flexibility also improved significantly, with greater accurate and conceptual responses and fewer perseverative errors on the WCST. These results align with evidence that tDCS over the dlPFC increases prefrontal excitability and supports set-shifting (Yuan et al., 2022). When combined with exergaming, which demands continual adaptation to changing contexts, the intervention likely promoted simultaneous engagement of executive and motor networks, enhancing cross-domain neuroplasticity (Tarr et al., 2022; Liang et al., 2022; Tsermentseli et al., 2022).

This study contributes to the growing evidence supporting NIBS in ASD, as prior research primarily examined tDCS or exergaming separately (Fang et al., 2019; Zhao et al., 2023; Liu et al., 2023a). Here, the combined intervention provides preliminary evidence that simultaneous neuromodulation and motor-cognitive training may yield greater improvements, suggesting a potential paradigm shift toward multimodal therapies targeting both cognitive and motor deficits (Pereira et al., 2024; Wang et al., 2023).

The observed synergistic effects may stem from tDCS lowering the threshold for synaptic plasticity in prefrontal regions, enhancing the learning benefits of exergaming. Motor training recruits prefrontal and parietal regions, that are involved in executive control, and increased cortical excitability in these areas may strengthen networks engaged during exergame play (Tsermentseli et al., 2022; Ludyga et al., 2022). This finding aligns with Hebbian principles, which hold that concurrent stimulation and activity-dependent learning facilitate long-term synaptic strengthening (Hebb, 2005).

Clinically, these findings are important because children with ASD often experience motor coordination deficits and executive function impairments that limit daily activities and social participation (Bhat et al., 2022; Fournier et al., 2020). The tDCS-exergaming combination provides a noninvasive, engaging intervention addressing both deficits, and the interactive nature of Kinect-based training may improve compliance and motivation (Fang et al., 2019; Pereira et al., 2024).

Study limitations

Several limitations should be acknowledged. The small sample size (n=30) restricts generalizability and effect stability, and the short intervention duration precludes conclusions about long-term maintenance (Kunz et al., 2023). The study included only high-functioning children aged 7–10, limiting applicability to other ages and ASD phenotypes (Lord et al., 2020). No neurophysiological measures (EEG, fMRI) were done to assess underlying brain mechanisms directly, and follow-up assessments were absent, preventing evaluation of the durability of improvements (Nair et al., 2020; Zhao et al., 2023). Optimal stimulation parameters for tDCS (electrode location, current intensity, session duration) remain to be determined, and individual responses may vary based on brain architecture, neurochemistry, and baseline cortical excitability (Bikson et al., 2022; Wang et al., 2023).

Study recommendations

Future studies with larger, more diverse samples, longitudinal follow-up, and neuroimaging are warranted to validate these findings and explore moderators of response (Uljarević et al., 2022). In particular, incorporating multimodal neuroimaging and electrophysiological assessments (e.g. EEG, fMRI, functional near-infrared spectroscopy) could help delineate the neural mechanisms underlying treatment-related motor and cognitive changes and clarify network-level targets for individualized stimulation protocols.

Conclusion

In conclusion, this study provides strong evidence that combining tDCS with exergaming enhances motor and cognitive outcomes in children with ASD. Targeting both corticocerebellar and prefrontal networks, this integrated approach holds promise for more effective and engaging neurorehabilitation interventions. Future research should confirm these effects and explore the long-term benefits of multimodal therapies for improving motor learning, ideally integrating neural profiling tools to link behavioral gains to network-level plasticity.

Ethical Considerations

Compliance with ethical guidelines

This study was approved by the Research Ethics Committee of Tehran University, Tehran, Iran (Code: IR.UT.SPORT.REC.1404.127).

Data availability

The dataset presented in this study can be requested from the corresponding author.

Declaration of generative AI and AI-assisted technologies in the writing process

No AI tool influenced the scientific content, data analysis, or conclusions of this work.

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Authors' contributions

All authors contributed equally to the conception and design of the study, data collection and analysis, interception of the results and drafting of the manuscript. Each author approved the final version of the manuscript for submission.

Conflict of interest

The authors declared no conflict of interest.

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