Accepted Manuscript

Accepted Manuscript (Uncorrected Proof)

Title: The Combined Effect of Active Video Games and Transcranial Direct Current Stimulation (tDCS) on balance and Cognitive Flexibility in Children with Autism Spectrum Disorder

Authors: Sepideh Fallahiyan¹, Mahmoud Sheikh¹, Seyyed Fardin Qeysari¹, Mahboubeh Ghayour Najaf abadi^{1,*}

1. Department of Behavioral and Cognitive Sports Sciences, Faculty of Sports and Health Sciences, University of Tehran, Tehran, Iran.

*Corresponding Author: Mahboubeh Ghayour Najaf abadi, Department of Behavioral and Cognitive Sports Sciences, Faculty of Sports and Health Sciences, University of Tehran, Tehran, Iran. Emial: m.ghayournaj@ut.ac.ir

To appear in: Basic and Clinical Neuroscience

Received date: 2025/09/16

Revised date: 2025/11/11

Accepted date: 2025/11/15

This is a "Just Accepted" manuscript, which has been examined by the peer-review process and has been accepted for publication. A "Just Accepted" manuscript is published online shortly after its acceptance, which is prior to technical editing and formatting and author proofing. Basic and Clinical Neuroscience provides "Just Accepted" as an optional and free service which allows authors to make their results available to the research community as soon as possible after acceptance. After a manuscript has been technically edited and formatted, it will be removed from the "Just Accepted" Web site and published as a published article. Please note that technical editing may introduce minor changes to the manuscript text and/or graphics which may affect the content, and all legal disclaimers that apply to the journal pertain.

Please cite this article as:

Fallahiyan, S., Sheikh, M., Qeysari, S.F., Ghayour Najaf abadi, M. (In Press). The Combined Effect of Active Video Games and Transcranial Direct Current Stimulation (tDCS) on balance and Cognitive Flexibility in Children with Autism Spectrum Disorder. Basic and Clinical Neuroscience. Just Accepted publication Jul. 10, 2026. Doi: http://dx.doi.org/10.32598/bcn.2026.8350.1

Abstract

Background: This study looked at the effects of combined transcranial direct current stimulation (tDCS) and exergaming therapy on balance and cognitive flexibility in children with Autism Spectrum Disorder (ASD).

Materials and Methods: A quasi-experimental randomized controlled trial 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 with the Movement Assessment Battery for Children-2 (MABC-2) and Wisconsin Card Sorting Test (WCST).

Results: ANCOVA findings showed significant between-group differences favoring the experimental group for static balance (F= 9.537, p < .001, partial η^2 = 0.128) and dynamic balance (F= 7.510, p < .001, partial η^2 = 0.158), with medium-to-large effect sizes. The results showed that the combined tDCS and exergym intervention had a stronger effect on improving cognitive flexibility than exergym 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 has promise for improving motor learning and functional results in children with neurodevelopmental problems.

Keywords: Autism spectrum disorder, Cognitive flexibility, Exergaming, Motor learning, Neurorehabilitation, Transcranial direct current stimulation

1. 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 four times more commonly than females (Loomes et al., 2017). The most current CDC 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 Autism Spectrum Disorder (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, DeMayo, & Guastella, 2019; Christakou et al., 2013), even among persons who do not have intellectual disabilities. Current diagnostic techniques prioritize behavioral observation with standardized instruments such the ADOS-2 (Lord et al., 202·) and DSM-5-TR criteria (American Psychiatric Association, 2022).

In recent years, there has been an increasing interest in non-invasive intervention techniques, including structured physical exercise and active video games (exergames), as viable alternative tactics to established therapy for children with Autism Spectrum Disorder. 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 considerably reduce repeated behaviors, possibly via emotional control processes and dopaminergic system modulation (Zhao et al., 2023).

Non-invasive brain stimulation (NIBS) has emerged as a possible treatment for children with autism spectrum disorder (ASD), with increasing data supporting its ability to modify aberrant neural pathways. Recent research has shown that techniques like 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 to -0.54) as well as improvements in executive functions (SMD = 0.59; 95% CI: 0.42 to 0.76) (Liu et al., 2023).

Emerging research shows that transcranial direct current stimulation (tDCS) may improve motor abilities and balance in children with ASD via neuromodulating corticocerebellar circuits. Recent randomized controlled trials show that anodal stimulation (1-2mA) 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 (fMRI rs-FC r=0.42-0.48), and normalization of sensorimotor mu-rhythm (8-13Hz) power in resting EEG (p<0.01).

Despite expanding data on the individual benefits of non-invasive brain stimulation and computer-based therapies, no study has looked into the synergistic potential of combining these techniques to improve neuro-motor functioning in children with Autism Spectrum Disorder (ASD). This study fills a key knowledge gap by determining whether a combination protocol of transcranial direct current stimulation (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 give empirical evidence for the development of tailored neuromodulation protocols capable of concurrently addressing cognitive and motor brain networks, resulting in more successful ASD therapy techniques.

2. Methodology

2-1. Research type

This quasi-experimental randomized controlled trial study employed a pretest–posttest control group design and included 30 children aged 7 to 10 years with Autism Spectrum Disorder (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).

2-2. 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. Exclusion criteria were: (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.

2-3. Material

2-3-1. Transcranial Direct Current Stimulation (tDCS) device:

The study used a transcranial direct current stimulation (tDCS) device (Active DOSS-2) delivering a constant 1.5 mA. The stimulation protocol consisted of six 20-minute sessions over four weeks, using saline-soaked sponge electrodes (25 cm²) positioned according to the international 10–20 EEG system. The anode was placed over the left dorsolateral prefrontal cortex (F3) and the cathode over the right supraorbital region (See Figure 1). For the sham condition, the device applied a standard 30-second ramp-up and fade-out procedure, after which stimulation was discontinued in order to imitate 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 based on internationally accepted tDCS guidelines and previous evid ence-based protocols.

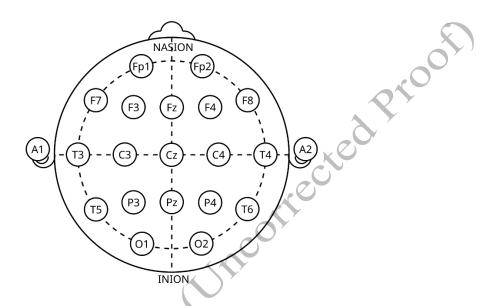


Figure \. Schematic illustration of the International 10–20 EEG electrode placement system

2-3-2. The Xbox One Gaming System:

The Xbox One was designed as a computer game console comparable to PlayStation systems, however it outperforms PlayStation models in terms of build quality and performance. The inclusion of Kinect technology adds a novel feature that allows players to control games only through body motions. 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 converted into the user's digital avatar in the game world, resulting in a dynamic and 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).

2-3-3. Kinect Motion Sensor:

This clever motion and audio detecting technology makes movement monitoring easier without requiring specific clothes or equipment. Kinect's excellent sensors allow it to perform precisely in a variety of lighting settings, from low light to strong light. Furthermore, the technique delivers extensive three-dimensional data on body joint positions, making it useful for movement analysis (Gao et al., 2014). 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., 2014).

2-3-4. Rivals Sports Installation Software:

Rivals is Xbox One-specific software. This program provides a varied range of sporting activities, such as 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, using innovative motion-sensing technologies that improve user involvement. Its advanced motion-tracking capabilities make it a desirable platform for lovers of simulated sports.

2-3-5. The Movement Assessment Battery for Children (MABC-2)

The Movement Assessment Battery for Children (MABC-2) was used in this study to evaluate the participants' balance abilities. This standardized exam was particularly useful for assessing static

and dynamic balance ability due to its well-validated balance subscale questions. 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, which was created in 1992 for children aged three to sixteen years. The age range is separated into three 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 gives accurate and useful data for detecting and categorising children's motor abilities, allowing professionals to plan appropriate therapeutic and educational treatments. 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 qualities, demonstrating strong reliability (Cronbach's alpha = 81%-90%), as well as validity for children with movement impairments.

2-3-6. The Wisconsin Card Sorting Test (WCST):

The WCST is a well-known neuropsychological diagnostic instrument that evaluates essential aspects of executive functioning, such as cognitive flexibility, abstract reasoning, and problem-solving ability. This standardized exam shows participants with 64 cards that change in three dimensions (color, shape, and number), and 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 validated the test's sensitivity (Heaton et al., 1993) and discriminant validity (Miyake et al., 2000) across varied groups, establishing it as an essential tool for both clinical neuropsychological examinations and cognitive neuroscience research.

2-3- V. Gilliam Autism Rating Scale - Third Edition (GARS-3):

The GARS-3 is a screening tool used to help identify signs and the severity of autism spectrum disorder (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 six 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

2-4. Prosedure

The study used a quasi-experimental randomized controlled trial design with two parallel groups. Initially, ethical approval (code: IR.UT.SPORT.REC.1404.127) was obtained from the Ethics Committee of the University of Tehran. 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 parents/legal guardians for each participant, and verbal assent was obtained from the children. Participation was voluntary, and families were informed that they could withdraw at any point without any consequence 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 autism spectrum disorder (ASD level 1), according to their medical records, were selected through convenience sampling. All participants in this study were diagnosed with high-functioning autism spectrum disorder based on the diagnostic criteria outlined in the Diagnostic and Statistical Manual of Mental Disorders (DSM-5). Participants were randomly assigned to either an experimental group (n=XX) or a control group (n=XX), with both receiving motion-based video game treatments via the Kinect system. The experimental group also received anodal transcranial direct current stimulation (tDCS) at 1.5 mA for 20 minutes over the left dorsolateral prefrontal cortex. The neurostimulation methodology entailed placing the anode electrode in the F3 region and the cathode electrode in the right supraorbital area, as per the worldwide 10-20 system. In the control group, the tDCS device was turned off automatically after 30 seconds to imitate a sham state.

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. The chosen video games were specially intended

to address both cognitive and motor components. Cognitive and motor tests were performed at both the baseline and post-intervention stages. Data analysis was carried out using suitable statistical techniques to investigate potential interaction effects between the therapies. This protocol was created to study the potential synergistic benefits of combining non-invasive brain stimulation and cognitive-motor training.

Table 1. Active Computer Game Training Protocol

First	For children with autism	Third	Playing the first and second sessions,
and	spectrum disorder, it is important	and	then commencing the second portion
second	to be familiar with the computer	fourth	of the clay tennis program.
session	program and explanations, to	session	
	play with the gadget, and to wind		
	up.		O
Fifth		Seventh	
and	Playing the third and fourth	and	Playing the fifth and sixth sessions
sixth	sessions before moving on to the	eighth	before moving on to the fourth stage
session	third stage of the clay tennis	sessions	of the clay tennis program, which is
	program, which is more		more challenging than the previous
	challenging than the previous	Y	level and requires more prior
	level and requires a deeper		knowledge.
	understanding of the previous		
270 7	stages.		
Ninth		Eleven	This phase involves conducting a
session	From session 8 and 9, you will	and	standardized virtual match that
And	proceed to stage 5 of the clay	twelve	rigorously applies official tennis
tenth	tennis program, which is more		regulations. The session will
session	challenging than the previous		implement the authentic scoring
	level if you have mastered the		system, enforce mandatory court-
	previous stages well, and the level of play varies depending on		side changes after odd-numbered games, and adhere to realistic match
	the quantity of play, progress, and		timing intervals. This structured
	individual differences.		approach is designed to enhance
	marviduai differences.		cognitive flexibility, rule adherence,
<i>></i>			and situational adaptation within an
			engaging digital environment. The
			simulation aims to translate acquired
			gaming skills into structured
			cognitive-behavioral outcomes.

2-6. Statistical analysis of data

The Shapiro-Wilk test was used to determine the normality of data distribution, and Levene's test was used to check the homogeneity of variances. After establishing the essential assumptions, an analysis of covariance (ANCOVA) was used to analyze within-group and between-group changes, with pretest scores serving as covariates. To assess differences within groups, paired samples t-tests were used. Statistical analyses were conducted using SPSS version 25, with a significance threshold of $\alpha = 0.05$. 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.

3- Results

3-1- Descriptive data

The table shows 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 such as 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.

Table *: Descriptive statistics of subjects							
Group	Numbe r	Age (year) Mean □ SD	Height (Cm) Mean □ SD	weight (Kg) Mean □ SD	Autism severity (Gars-3)		
Experimenta 1	15				56/15±3/9 4		
Sham	15	7.71 🗆 0.97	127.65	25.37	57/39±4/1		

3-2-1- 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 < .001, partial η^2 = .128), with the experimental group outperforming the control group. Similarly, dynamic balance also demonstrated a significant between-group difference (F= 7.510, p < .001, partial η^2 = .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 : Results of covariance analysis in static and dynamic balance variables							
Variable			Group F p-value				Effect size
<i>Y</i>	experimental		Control		coefficient		(η^2)
	Pre-test	Post-test	Pre-test	Post-test			
Static balance	$2.31(\pm 1.80)$	$3.60(\pm 1.80)$	$2.70(\pm 1.35)$	$1.70 (\pm 0.8)$	9,287	<0.001*	0.128
Dynamic	$1.79(\pm 0.7)$	$2.44(\pm 1.60)$	$0.86(\pm 0.50)$	$0.98(\pm 0.9)$	٧,۵١٠	<0.001*	0.158
Balance							

3-2-1- 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 = 6.540, p = 0.016, partial η^2 = 0.195). Similarly, conceptual answers in the combined group climbed significantly from 0.37 to 2.13, compared to the restricted rise in the exergame group (F = 7.221, p = 0.012, partial η^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, partial η^2 = 0.324). The combination intervention significantly improved cognitive performance compared to exergame alone (p < 0.05).

Table 4: Results of covariance analysis on cognitive flexibility variable							
Variable			Group	F	p-	Effect	
	ex	experimental		Control	coefficient	value	size
	Pre-test	Post-test	Pre-test	Post-test			(η^2)
Correct	19.17(±6.60)	29.05(±7.91)	18.90(±6.01)	18.89(±6.80)	9,04.	٠,٠١۶	٠,١٩۵
response							
Conceptual	$0.37(\pm 0.29)$	2.13(±1.19)	$1.49(\pm 0.49)$	1.97(±0.99)	٧,٢٢١	٠,٠١٢	٠,٢١١,
responses		0					
Perseverative	21.12(±7.89)	19.30(±8.18)	21.47(±8.09)	20.99(±6.989)	17,941	٠,٠٠١	٠,٣٢۴
Errors							

4- Discussion and conclusion

The current study examined the effects of combining transcranial direct current stimulation (tDCS) with exergaming on balance and cognitive flexibility in children with Autism Spectrum Disorder (ASD). Results showed substantial improvements in both static and dynamic balance and 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.

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 dorsolateral prefrontal cortex (DLPFC) may have enhanced top-down control of cerebellar-thalamic pathways, facilitating motor learning during exergaming (Liu et al., 2023). 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 Wisconsin Card Sorting Test. These results align with evidence that tDCS over the DLPFC increases prefrontal excitability and supports set-shifting (Liu et al., 2023; 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 noninvasive brain stimulation in ASD, as prior research primarily examined tDCS or exergaming separately (Fang et al., 2019; Zhao et al., 2023; Liu et al., 2023). 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 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 aligns with Hebbian principles, where concurrent stimulation and activity-dependent learning facilitate long-term synaptic strengthening (Hebb, 1949/2005).

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 non-invasive, 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).

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 collected to directly assess underlying brain mechanisms, 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). 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, fNIRS) could help delineate the neural mechanisms underlying treatment-related motor and cognitive changes and clarify network-level targets for individualized stimulation protocols.

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.

Acknowledgements

We are deeply grateful for our participants' resilience and unwavering commitment during the study, which spanned from the initial phase through to the end of the intervention period.

Data Availability

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

Declarations

The authors declare no conflicts of interest with regards to authorship, sponsorship, and funding.

Funding

The research did not obtain financial support from any specific funding body in different sectors.

References

American Psychiatric Association. (2022). *Diagnostic and statistical manual of mental disorders* (5th ed., text rev.; DSM-5-TR). Washington, DC: Author.

Bhat, A. N., Landa, R., & Galloway, J. C. (2022). Current perspectives on motor and cognitive impairments in children with autism spectrum disorder. *Developmental Neurorehabilitation*, 25(6), 341–354. https://doi.org/10.1080/17518423.2021.1894761

Bikson, M., Grossman, P., Thomas, C., Zannou, A. L., Jiang, J., Adnan, T., ... & Woods, A. J. (2022). Safety of transcranial direct current stimulation: Evidence based update 2016–2021. *Brain Stimulation*, *15*(5), 1100–1112. https://doi.org/10.1016/j.brs.2022.06.001

Cai, Z., Liu, C., Li, S., & Zhang, L. (2017). RGB-D datasets using Microsoft Kinect or similar sensors. *Multimedia Tools and Applications*, 76(4), 6813–6835. https://doi.org/10.1007/s11042-016-4237-6

Chen, S. F., et al. (2016). Deficits in executive functions among youths with autism spectrum disorders: An age-stratified analysis. *Psychological Medicine*, 46(8), 1625–1638. https://doi.org/10.1017/S0033291715002238

Christakou, A., et al. (2013). Disorder-specific functional abnormalities during sustained attention in youth with ADHD and ASD. *Molecular Psychiatry*, *18*, 236–245. https://doi.org/10.1038/mp.2012.49

Demetriou, E. A., DeMayo, M. M., & Guastella, A. J. (2019). Executive function in autism spectrum disorder: History, theoretical models, empirical findings, and potential as an endophenotype. *Frontiers in Psychiatry*, *10*, 753. https://doi.org/10.3389/fpsyt.2019.00753

Fang, Q., Aiken, C. A., & Li, L. (2019). Exergaming for children with autism spectrum disorder: A systematic review. *Games for Health Journal*, 8(2), 74–84. https://doi.org/10.1089/g4h.2018.0072

Fournier, K. A., Hass, C. J., Naik, S. K., Lodha, N., & Cauraugh, J. H. (2020). Motor coordination in autism spectrum disorders: A synthesis and meta-analysis. *Journal of Autism and Developmental Disorders*, 50(1), 1–21. https://doi.org/10.1007/s10803-019-04253-3

Gao, Z., Zheng, W., & Hwang, J. (2015). Leveraging two Kinect sensors for accurate full-body tracking. *International Conference on Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management.*

Ghayour Najafabadi, M., Saghaei, B., Shariat, A., Ingle, L., Babazadeh Zavieh, S. S., Shojaei, M., & Daneshfar, A. (2022). Validity and reliability of the Movement Assessment Battery for Children–Second Edition (MABC 2) test in children with and without motor impairment: A prospective cohort study. *Annals of Medicine and Surgery*, 77, 103672. https://doi.org/10.1016/j.amsu.2022.103672

Gilliam JE. GARS-3: Gilliam Autism Rating Scale—Third Edition. Pro-Ed Publishers Austin; 2014.

Hebb, D. O. (2005). *The organization of behavior: A neuropsychological theory*. Psychology Press. (Original work published 1949)

- Heaton, R. K., Chelune, G. J., Talley, J. L., Kay, G. G., & Curtiss, G. (1993). *Wisconsin Card Sorting Test Manual: Revised and Expanded*. Odessa, FL: Psychological Assessment Resources.
- Henderson, S. E., Sugden, D. A., & Barnett, A. L. (2007). *Movement Assessment Battery for Children–Second Edition (MABC 2) Examiner's Manual*. London: Pearson Assessment.
- Hondori, H. M., & Khademi, M. (2014). A review on technical and clinical impact of Microsoft Kinect on physical therapy and rehabilitation. *Journal of Medical Engineering*, 2014, 846514. https://doi.org/10.1155/2014/846514
- Kindregan, D., Gallagher, S., & Gormley, J. (2015). Gait deviations in children with autism spectrum disorders: A review. *Autism Research and Treatment*, 2015, 741480. https://doi.org/10.1155/2015/741480
- Kunz, M., Poustka, L., & Bölte, S. (2023). Clinical trials in autism spectrum disorder: Methodological challenges and recommendations. *Autism Research*, *16*(5), 849–861. https://doi.org/10.1002/aur.3005
- Liang, H., Zhang, X., & Qian, Y. (2022). Observational learning and cognitive flexibility in children with autism spectrum disorder. *Journal of Autism and Developmental Disorders*, 52(6), 2591–2604. https://doi.org/10.1007/s10803-021-05179-0
- Liu, H., Chen, X., & Li, F. (2023). Enhancing executive function in children with ASD using tDCS: Evidence from a randomized controlled trial. *Journal of Autism and Developmental Disorders*, 53(2), 560–574. https://doi.org/10.1007/s10803-022-05678-3
- Liu, T., Wang, Y., Zhang, Y., & Chen, H. (2023). Non-invasive brain stimulation in autism spectrum disorder: A systematic review and meta-analysis of randomized controlled trials. *Neuroscience* & *Biobehavioral Reviews*, 149, 105188. https://doi.org/10.1016/j.neubiorev.2023.105188
- Loomes, R., Hull, L., & Mandy, W. P. L. (2017). What is the male to female ratio in autism spectrum disorder? A systematic review and meta-analysis. *Journal of the American Academy of Child & Adolescent Psychiatry*, *56*(6), 466–474. https://doi.org/10.1016/j.jaac.2017.03.013
- Lord, C., Elsabbagh, M., Baird, G., & Veenstra-VanderWeele, J. (2020). Autism spectrum disorder. *The Lancet*, 395(10242), 908–922. https://doi.org/10.1016/S0140-6736(19)32500-0
- Ludyga, S., Gerber, M., & Pühse, U. (2022). Neural mechanisms of exercise-induced cognitive enhancement: The role of prefrontal and parietal cortex. *Neuroscience & Biobehavioral Reviews*, *134*, 104505. https://doi.org/10.1016/j.neubiorev.2021.12.012
- Maenner, M. J., Warren, Z., Williams, A. R., et al. (2023). Prevalence and characteristics of autism spectrum disorder among children aged 8 years Autism and Developmental Disabilities Monitoring Network, 11 sites, United States, 2020. *MMWR Surveillance Summaries*, 72(2), 1–19. https://doi.org/10.15585/mmwr.ss7202a1
- Nair, A., Treiber, J. M., Shukla, D. K., Shih, P., & Müller, R. A. (2020). Impaired thalamocortical connectivity in autism spectrum disorder: A study of functional and structural connectivity. *Brain*, *143*(5), 1586–1596. https://doi.org/10.1093/brain/awaa078
- Pereira, A. P. S., da Silva, N. M., & Oliveira, R. (2024). Effects of transcranial direct current stimulation on motor performance in children with neurodevelopmental disorders: A randomized

- controlled trial. *Journal of Autism and Developmental Disorders*. Advance online publication. https://doi.org/10.1007/s10803-024-06555-4
- Qeysari, S. F., Sheikh, M., Homanian, D., & Bagherzadeh, F. (2025). Comparing the Effects of Play-based Training and Therapeutic Horseback Riding on the Stanford Social Dimensions in Adolescents With Autism Spectrum Disorder: Examining the Theory of Social Motivation. The Scientific Journal of Rehabilitation Medicine, 14(1), 40-55. doi: 10.32598/SJRM.14.1.3279
- Tarr, B., Launay, J., & Dunbar, R. I. M. (2022). Exergaming, social cognition, and executive functions: A systematic review. *Frontiers in Psychology*, *13*, 879321. https://doi.org/10.3389/fpsyg.2022.879321
- Tsermentseli, S., Spain, D., & Powell, T. (2022). Neural mechanisms of executive function in autism spectrum disorder: Insights from neuroimaging. *Neuropsychologia*, *169*, 108199. https://doi.org/10.1016/j.neuropsychologia.2022.108199
- Uljarević, M., Hedley, D., Rose-Foley, K., & Richdale, A. L. (2022). Profiles of executive functioning in autism spectrum disorder and their clinical correlates. *Journal of Autism and Developmental Disorders*, 52(9), 3952–3965. https://doi.org/10.1007/s10803-021-05249-3
- Wang, Y., Jiang, Y., & Xu, G. (2023). Transcranial brain stimulation for autism spectrum disorder: Advances and challenges. *Frontiers in Psychiatry*, *14*, 989905. https://doi.org/10.3389/fpsyt.2022.989905
- Weimer, A. K., Schatz, A. M., Lincoln, A., Ballantyne, A. O., & Trauner, D. A. (2021). Motor impairment in autism spectrum disorder: A clinical perspective. *Pediatric Neurology*, *119*, 67–74. https://doi.org/10.1016/j.pediatrneurol.2021.02.007
- Yuan, J., Yang, Y., & Liu, Q. (2022). The effect of transcranial direct current stimulation on executive functions: Evidence from a meta-analysis. *Cortex*, 149, 26–41. https://doi.org/10.1016/j.cortex.2022.01.014
- Zhao, H., Li, Y., Sun, W., & Chen, J. (2023). Cerebellar transcranial direct current stimulation improves motor function in children with autism spectrum disorder: A randomized controlled trial. *Neurorehabilitation and Neural Repair*, *37*(6), 455–466. https://doi.org/10.1177/15459683231154738
- Zhu, X., Li, Y., & Chen, H. (2021). Exergame interventions and their effects on children's executive function: The role of physical intensity and cognitive engagement. *Acta Psychologica Sinica*, 53(5), 505–514. https://doi.org/10.3724/SP.J.1041.2021.00505