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Systematic Review

Effects of Exergaming on Executive Functions in Children and Adolescents With Neurodevelopmental Disorders: A Three-Level Meta-Analysis

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Abstract

Background: Executive function deficits are a core feature of neurodevelopmental disorders in children and adolescents. Exergaming, an emerging intervention that integrates physical exercise with cognitive stimulation, may improve executive function; however, findings to date have been mixed. This meta-analysis synthesizes the available evidence to estimate overall effects and examine potential moderators. **Methods**: We systematically searched Web of Science, PubMed, Embase, the Cochrane Library, and Cumulative Index to Nursing and Allied Health Literature (CINAHL). Effect sizes were calculated as Hedges' g, and three-level random-effects models were fitted using the metafor package in R. **Results**: Eight articles from five countries (313 participants) were included. Exergaming significantly improved executive function in children and adolescents with neurodevelopmental disorders (overall effect: Hedges'g [g] = 0.48, p = 0.03; heterogeneity: Cochran's Q statistic [Q] = 118.71, $p < 0.001$). Moderator analyses suggested larger benefits for developmental coordination disorder (DCD; g = 1.87, $p < 0.05$) and autism spectrum disorder (ASD; g = 0.48, $p < 0.05$). Improvements were primarily observed in inhibitory control (g = 0.28, $p < 0.05$) and cognitive flexibility (g = 0.44, $p < 0.05$). **Conclusions**: Current low-quality evidence suggests that exergaming may yield small-to-moderate improvements in executive function in children and adolescents with neurodevelopmental disorders, with effects most evident in ASD and DCD and largely confined to inhibitory control and cognitive flexibility. However, exergaming has not shown clear advantages over active control interventions, and the limited number of trials and substantial heterogeneity warrant cautious interpretation and confirmation in larger, rigorously designed randomized controlled trials. **The PROSPERO Registration**: CRD420251163791; https://www.crd.york.ac.uk/PROSPERO/view/CRD420251163791.

Keywords: exergaming; neurodevelopmental disorders; executive function; child; adolescent; meta-analysis

Main Points

1. Exergaming showed significant improvements in executive function in children and adolescents with neurodevelopmental disorders, with a pooled effect size of g = 0.48, suggesting a small-to-moderate improvement overall.

2. The largest benefits from exergaming were observed in children with developmental coordination disorder (DCD), with a significantly higher effect size (g = 1.87) compared to those with autism spectrum disorder (ASD) and attention-deficit/hyperactivity disorder (ADHD).

3. Cognitive flexibility and inhibitory control showed the most consistent improvements following exergaming, whereas working memory and attention showed negative effects, suggesting that exergaming may confer domain-specific benefits in executive function.

4. Exergaming did not show significant advantages over active control interventions such as cognitive training, suggesting that while beneficial, it may not offer additional benefits beyond other active approaches.

1. Introduction

Neurodevelopmental disorders (NDDs) comprise a group of neurological and psychiatric conditions that typically emerge in childhood or adolescence [1]. According to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5), NDDs include attention-deficit/hyperactivity disorder (ADHD), autism spectrum disorder (ASD), motor disorders (e.g., developmental co-

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ordination disorder and tic disorders), intellectual disability, communication disorders, and specific learning disorders [2]. Although NDDs are highly heterogeneous in clinical presentation, etiology, and treatment response, they also show substantial symptom overlap [1], which may reflect shared risk factors and convergent molecular and neural mechanisms [3]. This overlap supports considering these conditions within a broader diagnostic category [1]. The prevalence of NDDs in children and adolescents has been reported to be as high as 18.3% [4]. Beyond their defining symptoms, NDDs are frequently accompanied by cognitive impairments, particularly in executive function [1].

Executive function (also termed executive control or cognitive control) refers to top–down mental processes that support goal-directed behavior when attention must be sustained and responses must be deliberate rather than automatic [5,6,7]. Its core components include inhibitory control, working memory, and cognitive flexibility [8]. Inhibitory control (inhibition) is the capacity to regulate attention, thoughts, behavior, and emotion to resist impulses and distractions and respond appropriately [9]. Working memory (updating) involves maintaining information and manipulating it mentally [8]. Cognitive flexibility (shifting), which builds on inhibition and working memory, reflects the ability to switch between tasks or mental sets and adapt efficiently to changing demands [10]. Beyond these core components, executive function also includes other subdomains, such as planning, attention, and verbal fluency [11,12].

Executive dysfunction is common in children with NDDs. For example, 89% of children with ADHD show at least one objectively measured executive function impairment, and working memory deficits have been reported in up to 62% [13]. Children with working memory impairment are also more likely to exhibit inattention and hyperactivity/impulsivity symptoms than those without such deficits [13]. Longitudinal evidence further suggests that executive-function difficulties may emerge early and predict later ADHD- and ASD-related traits [14]. Children with poorer executive function may have less capacity to compensate for early risk factors [15], whereas stronger executive function may confer greater neural adaptability and reduce the likelihood of an eventual NDD diagnosis [15]. Collectively, these findings imply that improving executive function may help alleviate symptoms and functional difficulties in children with NDDs. Executive function deficits may also contribute to poor emotion regulation, difficulties sustaining attention, limited spontaneous verbal expression, disorganized cognition, and reduced flexibility in managing multiple tasks [1,11,16,17]. Thus, enhancing executive function in this population is a key clinical and developmental goal.

Exergaming is a relatively new exercise modality informed by the theory of planned behavior and the cognitive enrichment hypothesis [18,19]. Using screens, motion sensors, and cameras, exergaming integrates physical activity with cognitively engaging tasks in virtual or game-based environments, with the aim of improving both physical and cognitive outcomes [20]. Common platforms include Dance Dance Revolution, Xbox Kinect, and Nintendo Wii. Exergaming has been widely studied as an approach to support cognition and executive function in older adults [21,22,23]. To date, only one meta-analysis has evaluated the effects of exergaming on executive function (inhibitory control, working memory, and cognitive flexibility) in children and adolescents [24]. That study provided an initial quantitative summary in youth with neurodevelopmental disorders and reported generally nonsignificant and inconsistent findings across executive-function domains. Specifically, it found nonsignificant effects on working memory (Hedges'g [g] = –0.70, $p > 0.05$) and cognitive flexibility (g = 0.31, $p > 0.05$) in youth with ADHD, and a nonsignificant effect on working memory in youth with ASD (g = 0.10, $p > 0.05$) [24]. These results contrast with more recent studies reporting executive-function gains following exergaming in children and adolescents with NDDs [25,26]. In addition, the prior meta-analysis examined only sample type as a moderator and did not evaluate other potentially important moderators. Methodologically, its conventional two-level approach did not account for dependencies among multiple effect sizes, which can bias variance estimates and reduce the robustness of inferences.

Consequently, the effects of exergaming on executive function in children and adolescents with NDDs remain uncertain. Prior work has been limited by methodological constraints, small sample sizes, and inadequate statistical power. Moreover, potentially clinically relevant factors, including exergaming dose and other exercise prescription variables, have not been systematically examined, which limits translation to practice. To address these gaps, we conducted a meta-analysis in children and adolescents with NDDs using three-level models to account for dependent effect sizes and domain-specific moderator analyses to evaluate multiple executive-function domains. This approach aims to provide more robust evidence to inform targeted and effective interventions in this population.

2. Materials and Methods

This review follows the Preferred Reporting Items for Systematic Reviews and Meta Analyses Statement (PRISMA) guidelines [27]. The protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO) on October 8, 2025 (ID: CRD420251163791). Although registration occurred after the initial database search (completed on 30 September 2025), it was finalized before study selection and data extraction, ensuring that screening and extraction adhered to prespecified Population, Intervention, Comparison, Outcomes and Study (PICOS) criteria. The PRISMA checklist is provided in the **Supplementary Materials**.

2.1 Information Sources and Search Strategies

We searched PubMed (https://pubmed.ncbi.nlm.nih.gov/), Web of Science (https://www.webofscience.com/), Embase (https://www.embase.com/), the Cochrane Library (https://www.cochranelibrary.com/), and Cumulative Index to Nursing and Allied Health Literature (CINAHL, https://www.ebsco.com/products/research-databases/cinahl-database) from inception to 30 September 2025. Two researchers (PW, DL) independently performed the searches and cross-validated results. Discrepancies were resolved through discussion among PW, DL, and JH until consensus was reached. Full Boolean search strings (**Supplementary Table 1**) and database-specific outputs (**Supplementary Tables 2–6**) are provided in the **Supplementary Materials**.

2.2 Selection Criteria

Studies were screened and assessed per the PICOS framework to determine inclusion and exclusion.

(1) Participants: all participants were clinically diagnosed with NDDs or diagnosed with NDDs using relevant scales. For example, participants were diagnosed with an NDD according to International Statistical Classification of Diseases and Related Health Problems 10th Revision (ICD-10) or ICD-11 [28,29]; with ADHD according to DSM-4 or DSM-5 [30,31]; with ASD according to Childhood Autism Rating Scale, Third Edition (CARS-3) [32]; or with developmental coordination disorder (DCD) according to Movement Assessment Battery for Children, Second Edition (MABC-2) [33], etc. If the mean age of participants in a study was between 6 and 18 years, the study was included even if a small number of participants fell outside this range [34].

(2) Intervention: the intervention was Exergaming. Exergaming is defined as integrating physical exercise with cognitive stimulation within a virtual reality or gaming environment using tools such as electronic screens, motion sensors, and cameras [35]. This approach relies on advanced technologies to track participants' body movements or responses and feed these data back to the digital game system, thereby influencing game progression and interaction [36,37]. Common systems include Dance Dance Revolution, Xbox Kinect, and Nintendo Wii. We did not restrict the duration of each session or the weekly frequency, and we also included studies on acute exercise.

(3) Control: exergaming combines "exercise" and "gaming", and represents an extension of exercise [38]. To prevent overlapping effects across different interventions from contaminating the effect size on executive function (the study's outcome), control groups were not permitted to participate in exercise intervention programs. However, studies involving individual exercises, non-exercise interventions (e.g., puzzle games, cognitive training), and daily activities (e.g., psychotherapy, routine rehabilitation, or educational programs) were allowed.

(4) Outcomes: the outcome was executive function (inhibitory control, working memory, cognitive flexibility, and attention). Regardless of whether executive function was assessed using computerized paradigms or scales, we included studies as long as the content measured executive function. Notably, if the study's outcome was "cognitive function" but included executive function components, we extracted only the executive function–related components.

(5) Study design: randomized controlled trials (RCTs) or quasi-experimental designs with pre- and post-test assessments.

(6) Language: English.

(7) Publication type: peer-reviewed journal articles.

(8) Data: sufficient information to compute effect sizes.

(9) Population: human participants.

2.3 Study Selection and Data Processing

Study selection was performed in two stages. First, two researchers (PW, DL) agreed on the search approach, independently searched the databases, and removed duplicates. Titles and abstracts were then screened in EndNote X9 (Clarivate Analytics, Philadelphia, PA, USA) according to predefined criteria. Disagreements ($<1\%$) were resolved by discussion. In the second stage, full texts of potentially eligible studies were reviewed by a third researcher (JH), and exclusions were decided jointly by JH and DL through consensus.

Data were extracted independently by PW and DL (agreement: 96.86%). Discrepancies were resolved through discussion with JH. We extracted study identifiers (authors, year) and prespecified moderators. Moderators were classified according to the PICO framework into population, intervention, control, and outcome dimensions [39]. Definitions and coding rules are summarized in Table 1, with additional details in **Supplementary Materials 1.2 Data Extraction**.

2.4 Statistical Analysis

Because many studies reported multiple effect sizes, violating independence assumptions, we used three-level meta-analysis to handle dependence among effects [40]. We calculated Hedges' g following prior studies and guidelines [40,41,42,43]. Positive effect sizes indicate greater improvement in executive function in the exergaming group relative to controls. Effect sizes and variances were computed in Excel 2024 (Microsoft Corporation, Redmond, WA, USA) following Aksayli et al. (2019) [44]. Statistical analyses were performed in R version 4.4.2 (R Foundation for Statistical Computing, Vienna, Austria) using metafor [45]. Detailed computation and analysis steps are provided in **Supplementary Materials (1.3 Statistical analysis)**.

Table 1. Overview of moderator variables according to the PICO framework.

PICO	Moderator	Category
Population	Type of NDD	Attention-deficit/hyperactivity disorder (ADHD); autism spectrum disorder (ASD); developmental coordination disorder (DCD).
Intervention	Acute or chronic	Acute exercise (referring to a one-time, short-duration exercise intervention); Chronic exercise (referring to long-term, repeated exercise interventions).
Intervention	Training duration	≥720 minutes; <720 minutes.
Control	The control group	Active control group (participants received an additional non-exergaming training intervention); Passive control group (participants received no additional intervention and only took part in pretest and posttest assessments).
Outcome	The type of executive function	Executive function: Inhibitory control; Working memory; Cognitive flexibility; Attention.
Outcome	Evaluation metrics	Reaction time; Score.

NDD, neurodevelopmental disorder; PICO, Population, Intervention, Comparison, Outcomes.

2.5 Risk of Bias

Two researchers independently assessed risk of bias using the Cochrane Risk of Bias Tool 2 (RoB 2, Cochrane Bias Methods Group, London, UK). across five domains: bias due to the randomization process; deviations from intended interventions; missing outcome data; measurement of the outcome; and selection of the reported result [46]. Judgments were "low risk", "high risk", or "some concerns [46]". Disagreements were resolved by a third reviewer (JH) to a consensus.

2.6 Quality of Evidence

We evaluated certainty of evidence using the Grading of Recommendations, Assessment, Development, and Evaluations (GRADE) approach, considering study limitations, inconsistency, indirectness, imprecision, and publication bias [47]. Evidence was downgraded by one level for serious concerns and by two levels for very serious concerns, yielding overall ratings of high, moderate, low, or very low certainty [48].

3. Results

As shown in Fig. 1, we identified 1655 records and removed 217 duplicates. After title and abstract screening, 25 articles underwent full-text review, and eight studies met the inclusion criteria and were included in the quantitative synthesis. Across included trials, 313 children and adolescents participated (159 assigned to exergaming and 154 to control), with mean ages ranging from 8.30 to 14.29 years. Studies were published between 2018 and 2025 and were conducted in Iran (n = 3) [25,49,50], Switzerland (n = 2) [51,52], and Korea (n = 1) [53], Spain (n = 1) [26], and China (n = 1) [54]. Regarding clinical populations, four trials enrolled participants with ADHD, three with ASD, and one with DCD. Exergaming platforms included Xbox Kinect, Wii Fit, UINCARE, Xbox 360 Kinect games, Nintendo Switch, and Wii Sports. Although both RCTs and quasi-experimental studies were eligible, all included studies were RCTs and provided sufficient data to compute effect sizes; therefore, the present meta-analysis is based exclusively on RCT evidence. Detailed study characteristics are provided in **Supplementary Table 7**. With respect to potential confounding variables, only two trials assessed baseline physical activity and reported no between-group differences ($p > 0.05$) [51,52]. None of the included studies reported baseline gaming exposure or other cognitive training, precluding formal comparisons of these factors between groups.

3.1 The Overall Effect of Exergaming on Executive Function

To estimate the overall effect of exergaming on executive function, we synthesized all effect sizes regardless of control type. The three-level random-effects model indicated a significant overall effect (g = 0.51, 95% confidence interval [CI] [0.02, 1.00], 95% prediction interval [PI] [–0.93, 1.95], $p = 0.043$), and a two-level random-effects model yielded a comparable and significant estimate (g = 0.56, 95% CI [0.28, 0.83], 95% PI [–0.92, 2.03], $p < 0.001$). However, the prediction intervals for both models spanned zero, suggesting that future studies may observe null or even negative effects. Substantial heterogeneity was detected (Cochran's Q statistic (33) = 162.33, $p < 0.001$). To further characterize the overall findings, pooled effects were examined separately against passive and active control conditions (**Supplementary Table 8**). The effect of exergaming was significant when compared with passive controls, whereas no significant effect was observed when compared with active controls.

After excluding this effect size, the pooled estimate from the three-level model was slightly attenuated but remained significant (g = 0.48, 95% CI [0.04, 0.93], 95% PI [–0.81, 1.78], $p = 0.03$), as shown in Fig. 2. A similar pattern was observed in the two-level model (g = 0.48, 95% CI [0.25, 0.71], 95% PI [–0.69, 1.65], $p < 0.001$). Although exclusion of the outlier did not materially alter the overall conclusions, this effect size was removed from subsequent analyses to enhance robustness and minimize undue influ-

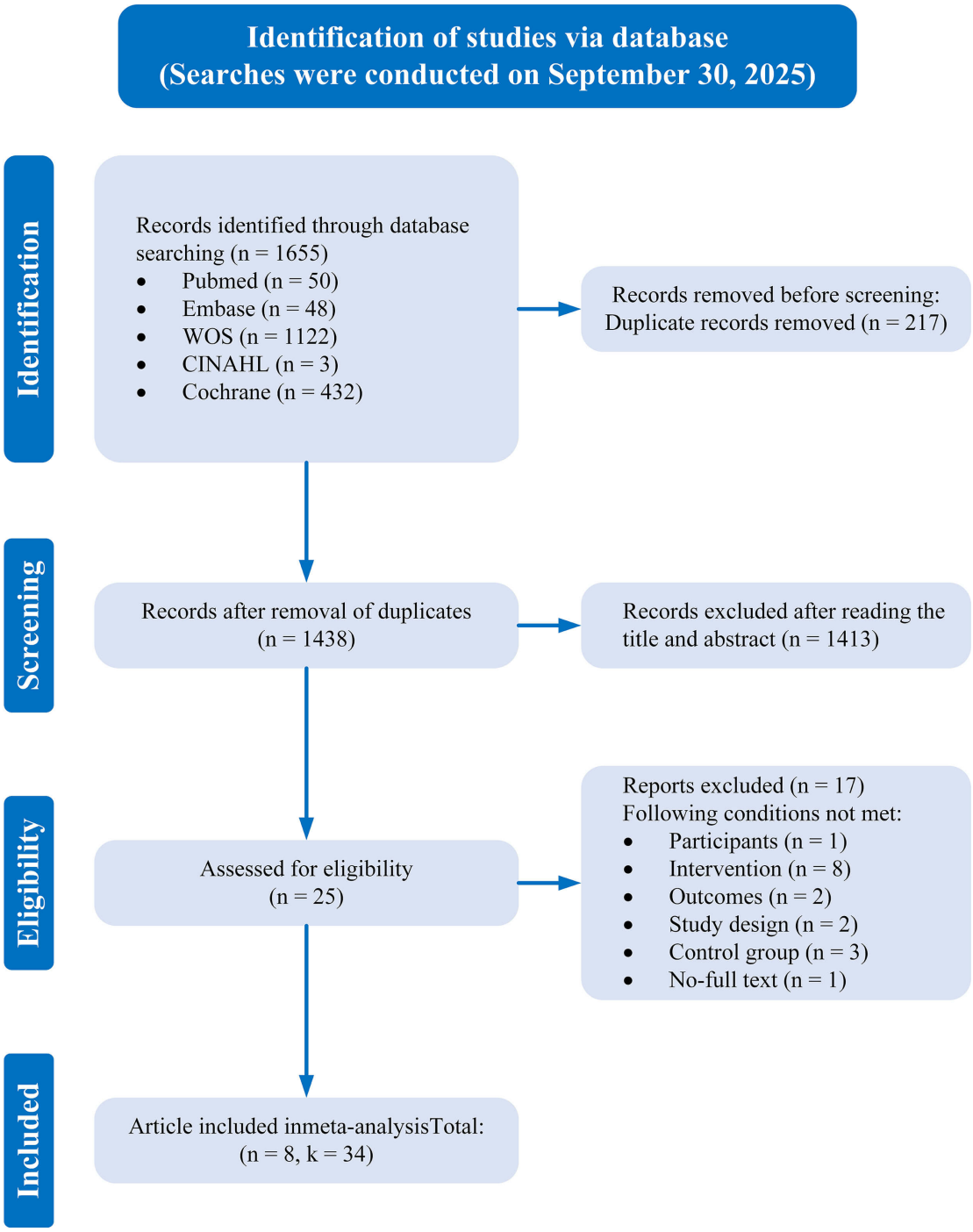


Fig. 1. PRISMA flow diagram of the study process. CINAHL, Cumulative Index to Nursing and Allied Health Literature; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta Analyses Statement; WOS, Web of Science.

ence (detailed results are shown in **Supplementary Table 9** and **Supplementary Fig. 1**).

3.2 Heterogeneity Analysis

After outlier removal, heterogeneity remained significant ($Q(32) = 118.71$, $p < 0.001$). Variance decomposition indicated that sampling variance (level 1) accounted for 23.46% of total variance, within-study variance (level 2) accounted for <1%, and between-study variance (level 3) accounted for 76.54%. Likelihood ratio tests indicated that level-2 variance was not statistically significant (Likelihood Ratio Test [LRT] <0.01, one-tailed $p > 0.49$), suggesting limited gain over a two-level model with level-2 variance constrained to zero. In contrast, level-3 variance was significant (LRT = 27.54, one-tailed $p < 0.001$), supporting the three-level model relative to a model without between-study variance. Despite the non-significant level-2 component, retaining the three-level structure remains appropriate

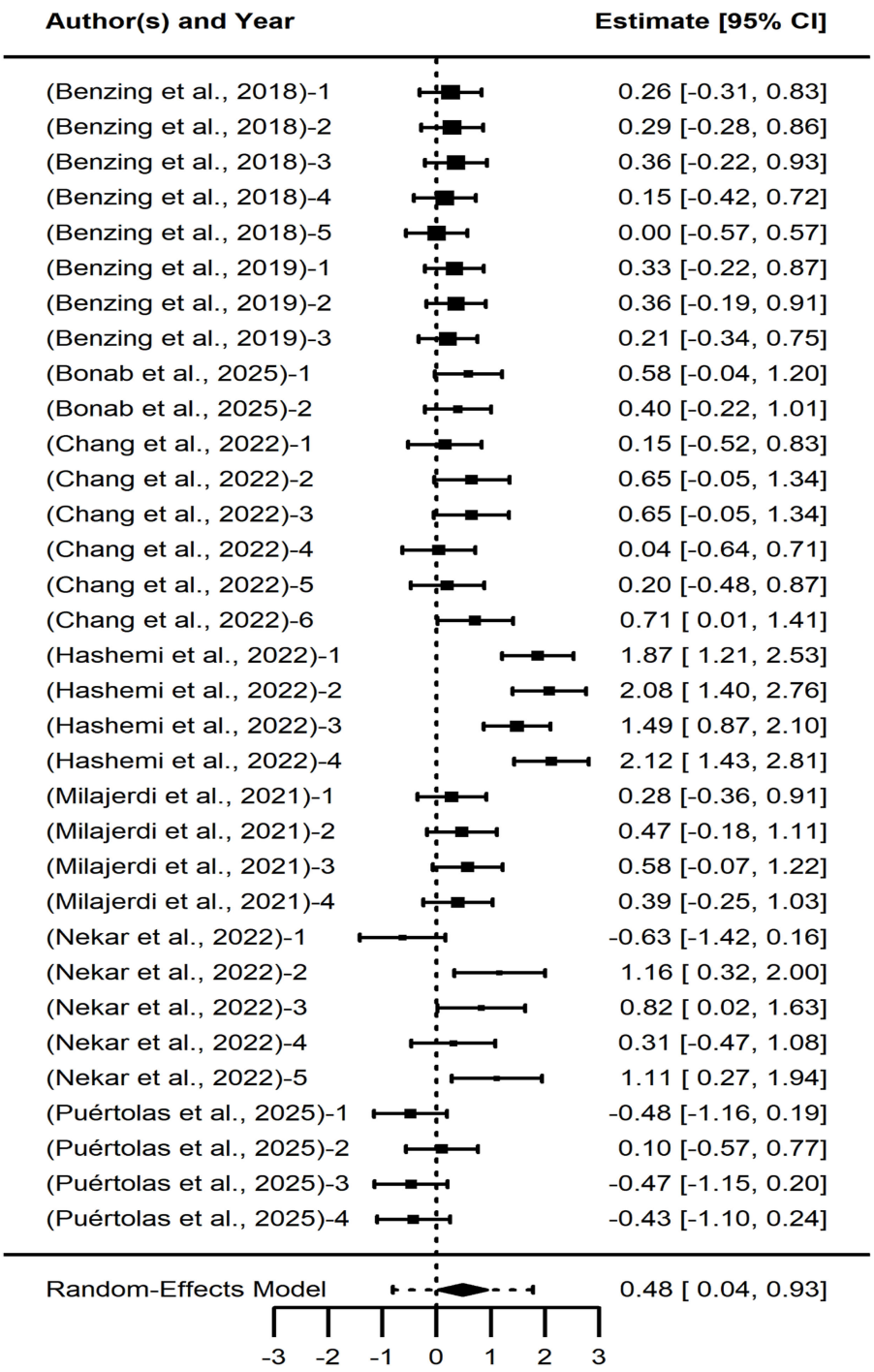


Fig. 2. The forest plot of the effect of exergaming on executive function (no outliers). Note: CI, confidence interval; the numbering following the references represents the order of the effect sizes within the study.

because it aligns with the data structure when multiple effect sizes are nested within studies [55].

3.3 Moderator Analysis

Moderator analyses identified two significant moderators (Fig. 3 and **Supplementary Figs. 2–8**). One study contributed effect sizes spanning multiple executive function domains (K = 5) and was therefore excluded from the domain-type moderator analysis [49]. Executive function domain significantly moderated intervention effects (F-statistic [F] (3, 25) = 5.13, $p = 0.007$), with the largest improvement observed for cognitive flexibility (g = 0.44, 95% CI [0.26, 0.62], $p < 0.001$). Pairwise comparisons indicated that effects for working memory (t(25) = –2.38, $p = 0.025$) and attention (t(25) = –3.44, $p = 0.002$) were smaller than those for cognitive flexibility, and attention effects were

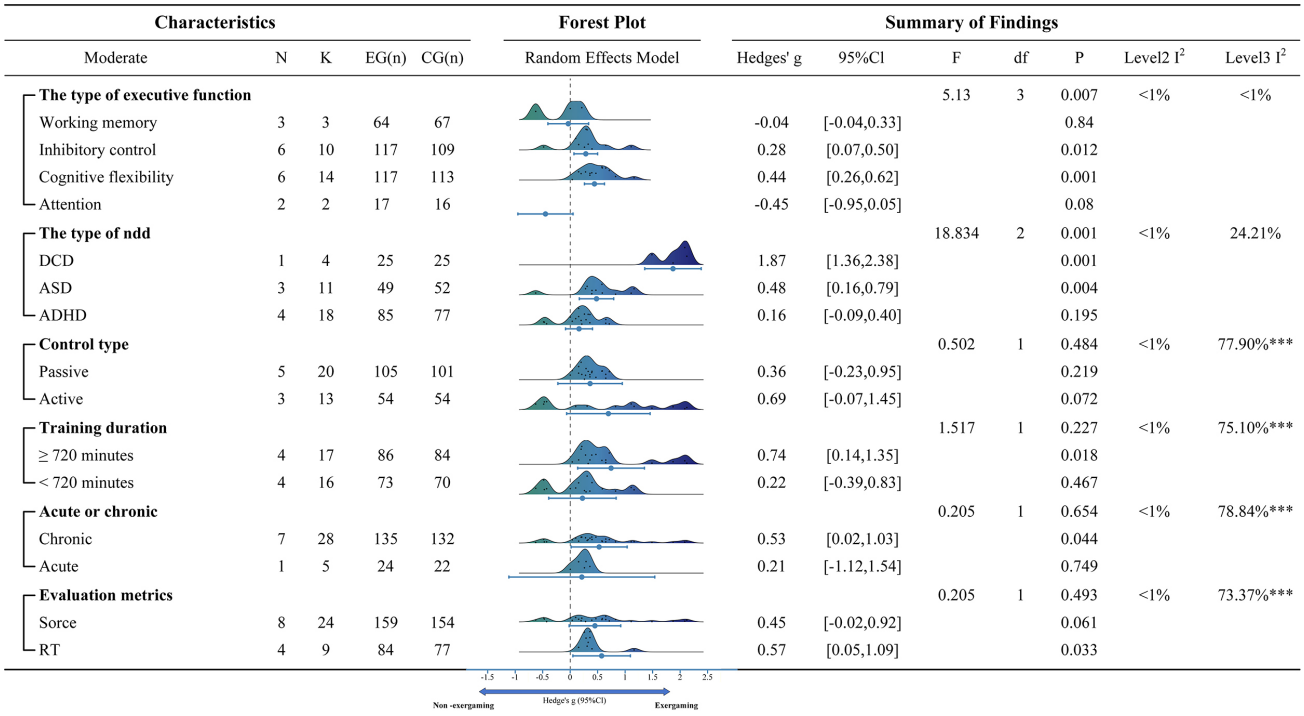


Fig. 3. Moderator analysis results for the effect of exergaming on executive function. RT, reaction time; K represents the number of effect sizes; n represents the sample size; N represents the number of studies; EG, experimental group; CG, control group. ***$p <$ 0.001.

also smaller than those for inhibitory control (t(25) = –2.77, p = 0.01). In addition, NDD type significantly moderated effects (F(2, 30) = 18.83, $p < 0.001$), with the largest effect observed in the DCD subgroup (g = 1.87, 95% CI [1.36, 2.38], $p < 0.001$); effects in ADHD (t(30) = –6.14, $p <$ 0.001) and ASD (t(30) = –4.73, $p < 0.001$) were significantly smaller than those in DCD.

3.4 Risk of Bias

Using RoB 2, six of eight studies (75%) were judged as having "some concerns" [25,26,49,51,53,54], and two (25%) were judged as "high risk" [50,52]. "Some concerns" ratings were primarily driven by incomplete reporting of randomization procedures (e.g., random assignment stated without describing sequence generation or allocation concealment) and the absence of preregistration in most studies, which limited assessment of selective reporting. The two "high risk" judgments reflected different issues. In one study, significant baseline group differences raised concerns about the randomization process and comparability. In the other, high risk was attributed to deviations from the intended intervention and missing outcome data: participants deviated from the prespecified protocol in ways that were not balanced across groups, and loss to follow-up exceeded 5%, with missingness likely related to true outcomes. Risk-of-bias summaries are provided in **Supplementary Figs. 9,10**.

3.5 Publication Bias

Publication bias was assessed via funnel plots [56], Egger's tests [57], and the trim-and-fill method [58]. The two-level model funnel plot showed some asymmetry (**Supplementary Fig. 11**). Egger's test in the two-level model suggested a low risk of publication bias (t(31) = 0.97, p = 0.34). A three-level Egger test with a modified predictor was non-significant (t(31) = –1.53, p = 0.14). Trim-and-fill analysis imputed three missing effects on the left side of the mean. After adjustment, the pooled effect remained significant and within the small-to-moderate range (g = 0.33, 95% CI [0.06, 0.60], p = 0.016) compared with the unadjusted estimate (g = 0.48, 95% CI [0.25, 0.71], $p < 0.001$) [59].

3.6 Level of Evidence Quality Assessment

Using GRADE, we rated the quality of evidence for executive function overall and for the inhibitory control and cognitive flexibility subdomains: (1) Executive function (overall): low-quality evidence. (2) Inhibitory control (subcategory): low-quality evidence. (3) Cognitive flexibility (subcategory): low-quality evidence. See **Supplementary Table 10** for details.

4. Discussion

This study systematically reviewed eight randomized controlled trials to evaluate the effects of exergaming interventions on executive functioning in children and adolescents with neurodevelopmental disorders, and to explore

potential moderators of intervention outcomes. Overall, the pooled estimate suggested a modest (small-to-moderate) improvement in executive functioning associated with exergaming, and the current evidence should be interpreted as preliminary. In addition, we identified two significant moderators: the type of executive function and the type of neurodevelopmental disorder, with the most consistent improvements observed for inhibitory control and cognitive flexibility, particularly among children and adolescents with autism spectrum disorder and developmental coordination disorder.

4.1 Effect of Exergaming on Executive Function

Exergaming was associated with statistically significant improvements in executive function in children and adolescents with neurodevelopmental disorders, although the pooled effect size was small and heterogeneity was substantial. Several findings warrant cautious interpretation. First, prediction intervals were wide and crossed zero, indicating that future studies may plausibly observe null or even negative effects. Second, among the 33 executive function effect sizes, only eight had confidence intervals excluding zero [49,53,54], with several others approaching significance [25,54]. Third, the overall certainty of evidence was rated as low (**Supplementary Table 10**), largely due to risk of bias and imprecision. When stratified by comparator type, exergaming was associated with significant benefits compared with passive controls (i.e., usual activities or no specific intervention) (overall effect: g = 0.34, p = 0.001), with high consistency across studies (Q = 7.29, p = 0.99). In contrast, exergaming did not show a statistically significant advantage over active control conditions such as cognitive training (overall effect: g = 0.7, p = 0.297; **Supplementary Table 8**) [26,49,53], suggesting that benefits may be attenuated when controls receive interventions that themselves improve executive function. This pattern was consistent with the primary trials: in the two studies using active comparators, both the exergaming and control groups improved significantly in executive function among autistic children and adolescents [26,53], whereas such improvements were not observed in passive control groups. Notably, although the pooled effect versus passive controls was significant, only one individual study's effect size reached statistical significance [54], likely reflecting limited power in individual trials rather than the absence of a true effect. By integrating evidence across studies, meta-analysis increases statistical power and yields more stable estimates, reducing the likelihood of Type II error attributable to small samples [59].

Overall, these findings suggest that exergaming may enhance executive functioning in children and adolescents with neurodevelopmental disorders, consistent with principles of neuroplasticity whereby neural structure and function can be shaped by experience and environmental input [60]. Executive function is supported largely by frontal networks, particularly circuits involving the prefrontal cortex [61]. The prefrontal cortex integrates multimodal sensory input via extensive reciprocal connections with sensory and motor regions and coordinates distributed brain systems, positioning it as a central hub for executive control [62]. Because direct neuroimaging and electrophysiological evidence in pediatric neurodevelopmental-disorder populations is limited, mechanistic inferences must be made cautiously. Studies in older adults with mild cognitive impairment have reported reduced prefrontal activation following exergaming, interpreted as increased neural efficiency [63,64]; however, extrapolation to children and adolescents with neurodevelopmental disorders is speculative. Accordingly, available evidence is insufficient to determine whether exergaming alters prefrontal activity or broader network dynamics during executive function tasks in this population. Given the low certainty of evidence (**Supplementary Table 10**), these conclusions require confirmation in larger, rigorously designed randomized controlled trials.

4.2 The Moderator

Moderator analyses indicated that exergaming effects vary by neurodevelopmental-disorder type and executive-function domain. Disorder type significantly moderated outcomes, with the largest effect observed in DCD. However, the DCD estimate (g = 1.87) was derived from a single trial (even after excluding an extreme outlier) and should therefore be interpreted as preliminary and hypothesis-generating rather than definitive. Executive function deficits in DCD may relate to disruptions in information-processing systems (e.g., visuoperception) [65,66,67]. Exergaming integrates physical training with gamified tasks, which may increase engagement and provide multisensory stimulation within a virtual environment, plausibly recruiting visuomotor and cognitive-control processes relevant to DCD. Nonetheless, these mechanistic explanations remain speculative given the limited evidence base. Exergaming may also increase neurotrophic factors associated with learning [68], which act as neuroprotectants, promote neurogenesis [66,68], and enhance synaptic plasticity in the dentate gyrus [65,69]. Although biologically plausible, direct neurobiological evidence in children and adolescents with DCD is scarce; future trials should evaluate these hypotheses using larger samples and mechanistic endpoints.

By contrast, effects were smaller in ASD and attenuated in ADHD, with no significant pooled benefit observed for ADHD. This pattern is broadly consistent with a previous conventional meta-analysis [24]. Notably, Kou et al. (2024) [24] reported significant improvements in inhibitory control among children with ADHD in subgroup analyses, whereas our ADHD estimate pooled outcomes across multiple executive-function types and therefore did not indicate a clear overall benefit. Methodological differences may partly explain these discrepancies. Conventional

two-level meta-analyses often either select a single effect size per study, which discards information, or treat multiple outcomes from the same study as independent, which violates the independence assumption and may underestimate standard errors. In contrast, our three-level model accounts for within-study dependence and incorporates all available outcomes, which may yield more conservative and potentially more robust inferences for ADHD. At the trial level, several measures did not show clear improvements in executive function in ADHD [51,52], and in one study, the control group outperformed the exergaming group on several outcomes [26]. These findings likely attenuated the pooled estimate.

The executive-function domain also significantly moderated effects. Exergaming improved inhibitory control and cognitive flexibility, whereas effects on working memory and attention were minimal or tended to be negative. This pattern is broadly consistent with prior research [70]. The significant gains in inhibitory control and cognitive flexibility may stem from the neural networks they rely on and the nature of the training. Inhibitory control is thought to depend mainly on prefrontal regulation of impulsive behavior [9]. During exergaming, players must make timely responses in fast, dynamic contexts while suppressing inappropriate or irrelevant actions to score points or complete tasks—processes that repeatedly reinforce PFC-related inhibitory functions [71]. Cognitive flexibility may benefit because exergames often require rapid switching of strategies or task sets in response to changing game demands [72], providing frequent opportunities for adaptive "cognitive switching". Flexibility is also supported by prefrontal and related regions (e.g., cingulate cortex) implicated in monitoring and adjusting behavior [71]. In contrast, working memory may be less responsive because it depends on more complex and distributed networks and may require more targeted training to improve [73]. For attention, evidence remains sparse, limiting mechanistic interpretation.

Beyond disorder type and executive function domain, other candidate moderators were not statistically significant. These null findings may reflect limited power and the small evidence base rather than the absence of true moderation. Although between-study heterogeneity decreased after accounting for disorder type and executive function domain, this pattern should be reevaluated as additional, higher-quality studies accumulate.

4.3 Study Limitations and Implications

To our knowledge, this is the first meta-analysis to evaluate exergaming effects on executive function in children and adolescents with neurodevelopmental disorders while simultaneously examining multiple moderators within a unified framework. Identification of disorder type and executive-function domain as moderators provides a basis for selecting intervention targets and tailoring programs. Clinically, the findings suggest that exergaming may be a promising adjunct to established interventions rather than a replacement, offering an engaging supplementary approach to support executive function development.

Several limitations warrant caution. First, the evidence base was small (eight trials), with modest sample sizes, limiting precision of between-study (level 3) variance estimates and reducing power for moderator analyses; thus, moderation findings should be regarded as exploratory. Second, the risk of bias was substantial: 75% of studies were rated as having some concerns and 25% as high risk, which lowers confidence in pooled estimates. Sensitivity analyses excluding high-risk studies were not feasible because too few studies and effect sizes would remain to support stable re-estimation, and residual bias cannot be excluded. Third, most trials did not quantify background physical activity or cognitive activities outside the intervention, which may have confounded or diluted between-group differences. Fourth, restricting inclusion to English-language publications may have introduced language bias. Fifth, prediction intervals crossed zero, indicating that future studies could plausibly observe null or opposite effects. Sixth, PROSPERO registration occurred after database searching, which may raise concerns about retrospective registration and potential selection bias, despite registration preceding screening and extraction. Finally, although we examined exercise-prescription parameters as moderators, conclusions were limited by the small number of studies and heterogeneous reporting. Future research should prioritize adequately powered, multisite randomized controlled trials with preregistered protocols, standardized executive-function batteries, and mechanistic outcomes. Trials should also use standardized exergaming protocols and include longer follow-up periods to assess the durability of effects.

5. Conclusions

Current low-quality evidence suggests that exergaming may be associated with small-to-moderate improvements in executive function in children and adolescents with neurodevelopmental disorders. However, exergaming did not demonstrate a significant advantage over active control interventions, indicating that its incremental benefit beyond established active programs remains uncertain. Benefits appear most consistent in autism spectrum disorder and developmental coordination disorder and are primarily observed in inhibitory control and cognitive flexibility. Given the limited number of trials and low overall certainty, these findings should be considered preliminary and require confirmation in larger, rigorously designed randomized controlled trials.

Abbreviations

NDDs, neurodevelopmental disorders; ADHD, attention-deficit/hyperactivity disorder; ASD, autism spec-

trum disorder; DCD, developmental coordination disorder; GRADE, Grading of Recommendations, Assessment, Development, and Evaluations; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta Analyses Statement; PROSPERO, International Prospective Register of Systematic Reviews; CINAHL, Cumulative Index to Nursing and Allied Health Literature; PICOS, Population, Intervention, Comparison, Outcomes and Study; RCTs, randomized controlled trials; RoB 2, Cochrane Risk of Bias Tool 2; CI, confidence interval; PI, prediction interval; LRT, Likelihood Ratio Test; Q, Cochran's Q statistic.

Availability of Data and Materials

The data are extracted from published studies and are available in the paper, and the datasets are not subject to restrictions.

Author Contributions

PW: Contributed substantially to the conception and design of the study; led the data collection and data processing; performed data analysis and interpretation. DL: Contributed to the conception and design of the study; participated in data collection and data processing; supervised the overall research process. JH: Contributed to the conception and design of the study; participated in data collection and data processing. YS: Participated in study supervision; provided methodological guidance. NS: Contributed to the conception of the study and the literature review; participated in data interpretation. HW: Contributed to the design of the study and the literature review; participated in data processing and interpretation. ZX: Contributed to the interpretation of data and the critical review of the manuscript; provided key academic feedback. ZZ: Contributed to data analysis and interpretation. RZ: Assisted with data interpretation and manuscript review; provided feedback on data presentation and interpretation. CZ: Contributed to the conception and design of the study; provided important intellectual input; participated in data interpretation, manuscript revision and final approval. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable.

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Conflicts of Interest

The authors declare no conflicts of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.31083/AP47880.

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