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Effects of Acute Cognitively Engaging Physical Activity on Executive Function Development in Children Aged 4–12 Years: A Systematic Review and Meta-analysis

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Abstract

Background

Acute cognitively engaging physical activity (CEPA) has been proposed as an intervention for improving executive function, but its effects in children remain uncertain. This systematic review and meta-analysis evaluated the immediate effects of acute CEPA on executive function in children and explored whether these effects varied according to exercise modality, intensity, session duration, and participant age.

Methods

PubMed, Web of Science, the Cochrane Library, Embase, EBSCOhost, and the China National Knowledge Infrastructure were searched from inception through June 28, 2026. Randomized trials comparing a single bout of CEPA with either a non-exercise control or physical activity involving lower cognitive engagement at a comparable intensity were included. Small-sample-corrected standardized mean differences (SMDs) and 95% confidence intervals (CIs) were pooled using random-effects models in RevMan 5.4 and Stata 15.0. Exploratory subgroup analyses were conducted by exercise modality, intensity, session duration, and age. Risk of bias and the certainty of evidence were assessed using RoB 2 and GRADE, respectively.

Results

Thirteen studies involving 1,117 children were included. Compared with control conditions, acute CEPA produced small improvements in overall executive function (SMD = 0.22, 95% CI 0.14–0.33; I^2 = 25%), inhibitory control (SMD = 0.22, 95% CI 0.11–0.33; I^2 = 0%), and working memory (SMD = 0.35, 95% CI 0.17–0.54; I^2 = 0%). The pooled effect on cognitive flexibility was not statistically significant (SMD = 0.22, 95% CI − 0.08–0.51; I^2 = 69%). Within-subgroup effects on inhibitory control were significant for both physical activity–based and exergaming interventions, for low- and moderate-intensity activity, and for sessions lasting more than 15 min. Effects on working memory were significant for physical activity–based interventions, moderate-intensity activity, and children aged < 8 years, whereas effects on cognitive flexibility were significant for exergaming and children aged ≥ 8 years. No formal between-subgroup tests were conducted; these findings are therefore exploratory.

Conclusions

Acute CEPA may produce small immediate improvements in executive function in children, with more consistent evidence for inhibitory control and working memory than for cognitive flexibility. Apparent variation according to exercise characteristics and age remains exploratory and requires confirmation through direct comparisons.

Trial registration:

The study protocol was prospectively registered with PROSPERO (registration number: CRD420261458285).

1. Introduction

Executive functions (EFs) are higher-order cognitive processes that regulate cognition and behavior during complex, goal-directed tasks. Their core components—inhibitory control, working memory, and cognitive flexibility—are partly distinct but interrelated and jointly support planning, reasoning, and problem-solving [1, 2]. EFs are integral to child development. Inhibitory control and working memory are associated with reading comprehension and later academic adjustment [3, 4], while inhibitory control develops alongside emotion regulation [5]. Poorer preschool EFs are associated with higher levels of depressive and anxiety symptoms at school age [6]. Poorer EFs are also linked to aggressive behavior [7], obesity [8], and the broad cognitive deficits characteristic of attention-deficit/hyperactivity disorder (ADHD) [9]. Childhood is a period of rapid EF differentiation and development, with each component following a distinct trajectory [10, 11]. During this period, prefrontal systems remain highly plastic and sensitive to experience [12], and various forms of training and activity may improve EFs [13, 14]. Identifying safe and feasible interventions that yield immediate cognitive benefits is therefore theoretically and practically important.

Acute physical activity can rapidly alter physiological and cognitive states and is widely used to examine the short-term plasticity of EFs. However, the evidence remains mixed. An earlier meta-analysis suggested selective benefits for certain EF components, particularly inhibitory control [15], whereas a recent systematic review and meta-analysis of preadolescent children found no significant overall effects on EF task accuracy or reaction time and reported substantial between-study heterogeneity [16]. Potential mechanisms include exercise-induced physiological arousal, catecholaminergic modulation, and changes in cerebral blood flow [17–19]. Nevertheless, research has focused primarily on quantitative exercise characteristics, particularly intensity and duration, while paying less attention to qualitative features such as movement context, rule complexity, and cognitive demands [20–22]. Activities imposing comparable physiological loads may therefore produce different cognitive outcomes. The extent to which an activity engages the targeted EF processes may help explain this variation.

Cognitively engaging physical activity (CEPA) embeds cognitive challenges—such as rule changes, strategic decision-making, memory updating, response inhibition, and task switching—within physical activity. It requires participants to allocate attention, monitor the environment, and adapt their behavior while moving [20–23]. Common forms include open-skill and team sports, cognitively demanding physical education lessons, and exergaming [22–25]. However, CEPA should be defined by its task design and cognitive demands rather than by the activity label alone. Theoretically, it may combine transient exercise-induced physiological activation with task-specific cognitive practice. The “facilitation–guidance” framework, derived from animal studies of neurogenesis, proposes that physical

activity increases the capacity for plastic change, whereas environmental enrichment or cognitive stimulation guides the survival and functional integration of newly generated neurons [26, 27]. This framework provides a theoretical account of how physical activity and cognitive stimulation may act synergistically.

Findings from individual studies of acute CEPA have also been mixed. Among male adolescents aged 13–16 years, exergaming with high cognitive engagement improved cognitive flexibility relative to intensity-matched exergaming with low cognitive engagement [25]. In contrast, no significant differences in flanker task performance were found among CEPA, physical activity with low cognitive engagement, and cognitively engaging sedentary activity in children aged 6–8 years [28]. In another study of 8-year-old children, greater cognitive engagement impaired shifting performance but did not affect updating or inhibitory control [29]. These findings suggest that the immediate effects of CEPA may be component-specific and may vary according to exercise modality, the balance between cognitive and physiological loads, session duration, and developmental stage. Because EFs develop rapidly throughout childhood, responses may also differ by age. Previous reviews have either combined acute and chronic physical activity interventions or failed to consider cognitive engagement as an explicit eligibility criterion, limiting the ability to determine the specific contribution of cognitively engaging components to executive function outcomes [15, 16, 20–22]. The overall effects of acute CEPA in children, its component-specific effects, and potential variations according to exercise modality, intensity, duration, and age therefore remain unclear.

This systematic review and meta-analysis synthesized evidence from randomized trials examining the immediate effects of acute CEPA on EFs in healthy children aged 4–12 years. We estimated its effects on overall executive function, inhibitory control, working memory/updating, and cognitive flexibility and explored patterns according to exercise modality, intensity, session duration, and age. This study aimed to clarify the consistency and boundary conditions of the available evidence and inform the design and implementation of acute CEPA interventions for children and future high-quality trials.

2 Methods

2.1 Information sources and search strategy

This systematic review and meta-analysis was reported in accordance with PRISMA 2020 and the PERSiST guidance for systematic reviews in exercise, rehabilitation, and sports science [30, 31]. The protocol was prospectively registered in PROSPERO (CRD420261458285), and the completed PRISMA 2020 checklist is provided in Supplemental Material 1.

The search strategy was based on the Population, Intervention, Comparison, Outcomes, and Study design (PICOS) framework and combined controlled vocabulary with free-text terms. PubMed, Web of Science, the Cochrane Library, Embase, EBSCOhost, and the China National Knowledge Infrastructure (CNKI) were searched from inception through June 28, 2026. Search terms covered children, cognitively

engaging physical activity, executive function, and randomized controlled trials. Complete database-specific search strategies are provided in Supplemental Material 2. Search reporting followed PRISMA-S [32], and search methods followed the Cochrane Handbook for Systematic Reviews of Interventions [33]. Reference lists of the included studies and relevant systematic reviews were also screened for additional eligible studies.

2.2 Eligibility criteria

Eligibility criteria were defined using the PICOS framework.

2.2.1 Inclusion criteria

(1) Population: Healthy children aged 4–12 years without diagnosed neurodevelopmental, psychiatric, or neurological disorders or disorders affecting physical development.

(2) Intervention: Acute CEPA, defined as a single bout of physical activity. Eligible interventions explicitly incorporated cognitive demands, such as rule changes, strategic decision-making, memory updating, response inhibition, or task switching, or objectively assessed the level of cognitive engagement.

(3) Comparison: A non-exercise condition, such as a wait-list control, seated rest, or usual health education, or repetitive physical activity performed at a comparable intensity but with lower cognitive engagement.

(4) Outcomes: At least one immediate postintervention measure of overall executive function, inhibitory control, working memory, or cognitive flexibility.

(5) Study design: Randomized parallel-group or cluster-randomized trials and crossover or within-subject trials with randomized condition orders.

2.2.2 Exclusion criteria

(1) Non-randomized designs, including quasi-experimental studies and uncontrolled single-group pretest–posttest studies;

(2) Studies without a cognitively engaging physical activity condition or in which its independent effect could not be isolated;

(3) Studies involving clinical populations, such as children with attention-deficit/hyperactivity disorder, autism spectrum disorder, or cerebral palsy;

(4) Studies for which no eligible outcome data could be obtained after conversion or contact with the authors;

(5) Conference abstracts, dissertations, reviews, protocols, and other non-original publications.

2.3 Study selection and data extraction

Records were imported into EndNote 20 (Clarivate) and deduplicated. Two reviewers independently screened titles and abstracts and assessed the full texts of potentially eligible reports. Reasons for full-text exclusion were documented, and disagreements were resolved through discussion.

Using a prespecified form, two reviewers independently extracted: (1) author, publication year, and country; (2) participant age and sample size; (3) activity modality, exercise intensity, and session duration; (4) comparator; (5) executive function measure and outcome domain—inhibitory control, working memory/updating, or cognitive flexibility; and (6) data required to calculate effect sizes. Disagreements were resolved through discussion. Data extraction, intervention classification, and data conversion followed the Cochrane Handboo [33].

Preintervention and immediate postintervention means (M) and standard deviations (SDs) were extracted. When change scores were unavailable, the mean change and its SD were calculated as follows:

$$M_{change} = M_{post} - M_{pre}$$

$$SD_{change} = \sqrt{{SD_{pre}}^2 + {SD_{post}}^2 - 2r \times SD_{pre} \times SD_{post}}$$

where rr is the correlation between preintervention and postintervention measurements. When unreported, rr was set to the prespecified value of 0.50. Standard errors, 95% confidence intervals, and other convertible statistics were converted to M and SD according to the Cochrane Handbook [33].

Intervention characteristics and participant age were coded using prespecified categories. Activity modality was classified as exergaming or non-digital physical activity. Exergaming comprised interactive physical activities delivered through digital devices with real-time feedback. Non-digital physical activity included physically active games, team-based tactical activities, and motor–cognitive dual tasks performed without video game equipment [20–22, 25].

Exercise intensity was classified according to the relative-intensity criteria of the American College of Sports Medicine (ACSM) [34]. Given the distribution of lower-intensity comparisons, the ACSM very light and light categories were combined as low intensity (< 64% of maximal heart rate [HRmax]); moderate intensity was defined as 64%–76% HRmax and high intensity as ≥ 77% HRmax. When studies reported only absolute heart rate or qualitative intensity labels, two reviewers classified intensity using the definitions provided by the original authors. Comparisons with insufficient information were coded as unclear.

Based on previous meta-analyses and the distribution of intervention durations [35], sessions were classified as short (≤ 15 min), medium (> 15–25 min), or long (> 25 min). Because durations for working memory and cognitive flexibility were concentrated around 20 min, duration-based subgroup analyses were restricted to inhibitory control. Study samples were classified by mean age as younger (< 8 years)

or older (≥ 8 years), based on the developmental characteristics of executive function and the sample distribution [10, 11, 36]. This cutoff was used only for exploratory stratification.

For cluster-randomized trials that did not account for clustering, effective sample sizes were adjusted using a design effect calculated from the mean cluster size and intraclass correlation coefficient. When essential data could not be derived, study authors were contacted by email up to twice. Unavailable data were omitted only from the relevant quantitative synthesis; other eligible outcomes from the same study were retained.

2.4 Outcome measures

Primary outcomes were immediate postintervention measures of overall executive function, inhibitory control, working memory/updating, and cognitive flexibility. Outcomes were reported as reaction time, accuracy, or task scores. For measures in which lower values indicated better performance, the relevant means or mean changes were multiplied by − 1, while SDs remained unchanged. Thus, positive standardized mean differences (SMDs) favored CEPA. SMDs were used because measurement instruments varied across studies.

2.5 Risk of bias in included studies and certainty of evidence

Two reviewers independently assessed risk of bias for each outcome using the Cochrane risk-of-bias tool for randomized trials (RoB 2) [37]. Five domains were evaluated: the randomization process, deviations from intended interventions, missing outcome data, outcome measurement, and selection of the reported result. Overall judgments were classified as “low risk,” “some concerns,” or “high risk.” Disagreements were resolved through discussion.

Two reviewers independently assessed the certainty of evidence for inhibitory control, working memory, and cognitive flexibility using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach [38]. Evidence from randomized trials started at high certainty and could be downgraded for risk of bias, inconsistency, indirectness, imprecision, or publication bias. Final ratings were high, moderate, low, or very low. Disagreements were resolved by consensus.

2.6 Statistical analysis

Analyses were conducted using Review Manager 5.4 and Stata 15.0. Because all outcomes were continuous and measurement instruments varied across studies, pooled effects were expressed as small-sample-corrected standardized mean differences (SMDs) with 95% confidence intervals (CIs). Statistical significance was set at $P < 0.05$. Absolute SMDs of approximately 0.2, 0.5, and 0.8 were interpreted as small, moderate, and large, respectively [39].

Random-effects models were used because clinical and methodological heterogeneity was expected in participant age, intervention characteristics, and outcome measurement. Heterogeneity was quantified using I^2 and interpreted alongside the direction of effects and clinical and methodological differences

across studies. I^2 values of approximately 25%, 50%, and 75% indicated low, moderate, and high heterogeneity, respectively [40].

For syntheses including at least 10 studies, funnel plots and Egger's and Begg's tests were used to assess small-study effects and potential publication bias [41]. When funnel plot asymmetry was detected, the trim-and-fill method was used to explore the potential influence of missing studies [42]. Prespecified exploratory subgroup analyses were conducted by exercise modality, intensity, session duration, and participant age. No formal tests of between-subgroup differences were conducted. Robustness was examined using leave-one-out analyses and analyses excluding studies at high overall risk of bias. Findings were considered robust when the direction, magnitude, and statistical significance of the pooled effects remained materially unchanged.

3. Results

3.1 Study selection

Database searches identified 7,396 records, and reference-list screening identified 17 additional records. After 2,836 duplicates were removed, 4,577 records underwent title and abstract screening. Seventy-four full-text reports were assessed for eligibility, of which 61 were excluded for reasons detailed in Supplemental Material 3. Thirteen studies were included in the quantitative synthesis. The selection process is presented in Fig. 1.

3.2 Characteristics of the included studies

The 13 included studies, published between 2012 and 2025, involved 1,117 healthy children aged 4–12 years [28, 29, 43–53]. Two studies included children younger than 7 years [47, 53], six primarily included children aged 7–10 years [28, 29, 46, 49, 50, 52], and five primarily included children aged 10–12 years [43–45, 48, 51]. Studies were conducted in Switzerland (n = 4) [29, 45, 48, 51], Greece (n = 2) [43, 50], Canada (n = 2) [28, 44], China (n = 2) [47, 53], the United States (n = 2) [49, 52], and the Netherlands (n = 1) [46].

All studies evaluated a single bout of CEPA lasting 10–45 min. Seven used non-digital physical activities, including physically active games, team-based games, and motor–cognitive dual tasks [28, 29, 43–46, 53], whereas six used exergaming [47–52]. Based on the ACSM criteria, eight studies included at least one moderate-intensity CEPA condition [28, 29, 44, 45, 47, 51–53], and five included at least one low-intensity condition [28, 29, 45, 49, 52]. Intensity could not be classified for one or more conditions in four studies because the required physiological or perceived-exertion data were unavailable [43, 46, 48, 50]. Because some studies included multiple CEPA conditions, these intensity categories were not mutually exclusive.

All 13 studies assessed inhibitory control [28, 29, 43–53], five assessed working memory [29, 44, 45, 47, 53], and six assessed cognitive flexibility [29, 43–45, 47, 50]. Detailed study characteristics are presented

in Supplemental Material 4.

3.3 Risk-of-bias and certainty-of-evidence assessments

Of the 13 included studies, 10 raised some concerns regarding overall risk of bias, two were judged to be at low risk, and one was judged to be at high risk. Concerns primarily arose from insufficient reporting of random-sequence generation or allocation concealment. Three studies raised some concerns regarding deviations from intended interventions because group allocation was known and information on trial-related deviations was insufficient. Jäger et al. [45] were judged to be at high risk in the missing-outcome-data domain, whereas the remaining studies were at low risk. Detailed judgments are provided in Supplemental Material 5.1 and summarized in Fig. 2.

GRADE indicated moderate-certainty evidence of beneficial effects on inhibitory control and working memory. Evidence for both outcomes was downgraded by one level for risk of bias because allocation concealment was insufficiently reported in some studies. No additional downgrading was applied for inconsistency, indirectness, imprecision, or publication bias. Evidence for cognitive flexibility was rated as low certainty after being downgraded by one level each for risk of bias and inconsistency. Detailed GRADE assessments are provided in Supplemental Material 5.2.

3.4 Effects of cognitively engaging physical activity on executive function in children

Figure 3 presents the pooled effects of acute CEPA on overall executive function and its core components. Compared with control conditions, acute CEPA produced small improvements in overall executive function (SMD = 0.22, 95% CI 0.14–0.33; I^2 = 25%), inhibitory control (SMD = 0.22, 95% CI 0.11–0.33; I^2 = 0%), and working memory (SMD = 0.35, 95% CI 0.17–0.54; I^2 = 0%). The pooled effect on cognitive flexibility was not statistically significant (SMD = 0.22, 95% CI − 0.08–0.51; I^2 = 69%) and showed substantial heterogeneity.

3.5 Exploratory subgroup analyses

Prespecified subgroup analyses examined exercise modality, intensity, session duration, and participant age. Results are summarized in Table 1, with corresponding forest plots in Supplemental Material 6. Because no formal between-subgroup tests were conducted, all subgroup findings are exploratory.

3.5.1 Exercise modality

Comparisons were classified as non-digital CEPA or exergaming. For inhibitory control, pooled effects were significant in both the non-digital CEPA subgroup (SMD = 0.21, 95% CI 0.05–0.37) and the exergaming subgroup (SMD = 0.24, 95% CI 0.08–0.39). For working memory, the effect was significant for non-digital CEPA (SMD = 0.36, 95% CI 0.16–0.57) but not exergaming (SMD = 0.30, 95% CI − 0.14–0.74). For cognitive flexibility, the effect was not significant for non-digital CEPA (SMD = 0.19, 95% CI − 0.21–0.58) but was significant for exergaming (SMD = 0.34, 95% CI 0.02–0.66).

3.5.2 Exercise intensity

For inhibitory control, pooled effects were significant at both low intensity (SMD = 0.25, 95% CI 0.02–0.47) and moderate intensity (SMD = 0.19, 95% CI 0.03–0.36). For working memory, the effect was significant at moderate intensity (SMD = 0.42, 95% CI 0.18–0.67) but not low intensity (SMD = 0.25, 95% CI − 0.04–0.54). Neither low-intensity (SMD = − 0.05, 95% CI − 0.68–0.58) nor moderate-intensity CEPA (SMD = − 0.09, 95% CI − 0.36–0.18) significantly affected cognitive flexibility.

3.5.3 Session duration

Because all working-memory comparisons and all but one cognitive-flexibility comparison used 20-min sessions—the exception lasted 19.5 min—duration-based analyses were restricted to inhibitory control. Sessions were classified as short (≤ 15 min), medium (> 15–25 min), or long (> 25 min). Pooled effects were significant for medium-duration (SMD = 0.20, 95% CI 0.07–0.32) and long-duration sessions (SMD = 0.40, 95% CI 0.05–0.75), but not for short sessions (SMD = 0.20, 95% CI − 0.17–0.56).

3.5.4 Participant age

Study samples were classified by mean age as younger (< 8 years) or older (≥ 8 years). For inhibitory control, the effect was significant in the older subgroup (SMD = 0.25, 95% CI 0.12–0.38) but not the younger subgroup (SMD = 0.09, 95% CI − 0.15–0.33). For working memory, the effect was significant in the younger subgroup (SMD = 0.46, 95% CI 0.22–0.70) but not the older subgroup (SMD = 0.19, 95% CI − 0.11–0.48). For cognitive flexibility, the effect was significant in the older subgroup (SMD = 0.42, 95% CI 0.13–0.71) but not the younger subgroup (SMD = − 0.16, 95% CI − 0.62–0.30).

Table 1
Results of Subgroup Analysis.

Factor	Subgroup	Inhibitory control		Working memory		Cognitive flexibility	
		95% CI	P	95% CI	P	95% CI	P
Exercise modality	Physical activity	0.05, 0.37	0.01	0.16, 0.57	< 0.01	-0.21, 0.58	0.35
	Exergaming	0.08, 0.39	< 0.01	-0.14, 0.54	0.19	0.02, 0.66	0.04
Exercise intensity	Low	0.02, 0.47	0.03	-0.04, 0.54	0.09	-0.68, 0.58	0.87
	Moderate	0.03, 0.36	0.02	0.18, 0.67	< 0.01	-0.36,0.18	0.51
Session duration	Short	-0.17, 0.56	0.29	-	-	-	-
	Medium	0.07, 0.32	< 0.01	-	-	-	-
	Long	0.05, 0.75	0.02	-	-	-	-
Participant age	Younger	-0.15, 0.33	0.49	0.22, 0.70	< 0.01	-0.62, 0.30	0.49
	Older	0.12, 0.38	< 0.01	-0.11, 0.48	0.22	0.13, 0.71	< 0.01

3.6 Publication bias and sensitivity analyses

Funnel plots were generated for inhibitory control, working memory, and cognitive flexibility, and Egger's and Begg's tests were performed. Visual inspection of the funnel plots (Supplemental Material 7.1), together with the test results (Supplemental Material 7.2), indicated potential publication bias for cognitive flexibility (P = 0.038). The trim-and-fill method was used to explore the potential influence of unpublished studies. Two potentially missing studies were estimated, resulting in an adjusted pooled effect of 0.084 (95% CI: −0.225 to 0.392). This finding remained consistent with the primary analysis, indicating that the result was robust (Supplemental Material 7.3).

The magnitude, statistical significance, and direction of the pooled effects did not change materially in either sensitivity analysis (Supplemental Material 8). The findings remained unchanged after the leave-one-out analysis and the exclusion of studies judged to have a high overall risk of bias: inhibitory control (SMD = 0.24, 95% CI: 0.12 to 0.36; P < 0.01), working memory (SMD = 0.43, 95% CI: 0.21 to 0.66; P < 0.01), and cognitive flexibility (SMD = 0.28, 95% CI: −0.11 to 0.66; P = 0.16). These findings indicate that the meta-analytic results were relatively robust.

4 Discussion

4.1 Main Findings

This systematic review and meta-analysis synthesized evidence from randomized trials examining the immediate effects of a single CEPA bout in healthy children aged 4–12 years. Acute CEPA produced a small improvement in overall executive function. Benefits for inhibitory control and working memory were supported by moderate-certainty evidence, whereas the effect on cognitive flexibility was nonsignificant and supported by low-certainty evidence. Exploratory subgroup patterns suggested that effects may vary with the balance between physical load and cognitive challenge and with the alignment between activity demands and children's developmental level.

Previous meta-analyses generally reported cognitive benefits of CEPA, but Song et al. focused primarily on longer-term interventions, whereas Mao et al. combined acute and longer-term interventions [54, 55]. Broader reviews of physical activity in children also reported benefits for cognition and executive function, but showed substantial heterogeneity in intervention duration, activity content, cognitive engagement, and outcome measurement [56, 57]. By focusing on immediate outcomes after a single CEPA bout and analyzing the three EF components separately, the present study provides more specific evidence of component-level effects. However, the subgroup findings remain exploratory. The limited number of studies, lack of direct parameter comparisons, and absence of formal between-subgroup tests preclude conclusions about optimal intervention parameters or individualized exercise prescriptions.

4.2 Effects of acute CEPA on executive function

The immediate effects of acute CEPA may reflect the interaction between exercise-induced arousal and task-specific cognitive stimulation. A single bout of physical activity can transiently alter alertness, catecholaminergic activity, and information processing [17, 35, 58, 59], while CEPA repeatedly engages executive control through rule maintenance, cue monitoring, response inhibition, and behavioral adjustment [21, 22]. These benefits are unlikely to increase linearly with load: excessive physical load may constrain prefrontal resources [60], exercise intensity may affect processing speed and accuracy differently [61], and dopaminergic regulation of working memory and cognitive control may follow an inverted-U pattern [62]. Acute CEPA may therefore depend on the balance among physiological arousal, cognitive engagement, and available resources rather than on energy expenditure alone.

Benefits for inhibitory control may reflect process alignment between the intervention and assessment tasks. CEPA requires children to suppress prepotent responses, resist distraction, and select appropriate actions—processes central to inhibitory control tasks. Exercise and skill-learning theories emphasize repeated practice of goal maintenance, error monitoring, and action selection [63], while transfer is more likely when training and assessment tasks share processing demands [64, 65]. Improvements in inhibitory control may therefore arise from appropriate arousal, task-specific practice, and near transfer [14, 45].

Benefits for working memory may similarly reflect repeated demands on information maintenance and online updating. During CEPA, children retain rules, movement sequences, and spatial information while adapting their actions to environmental changes and feedback [21, 22, 63, 64]. A recent meta-analysis found that the benefits of acute physical activity over resting control conditions were most evident in working-memory accuracy, supporting this process-alignment explanation [66]. However, variation in task materials, cognitive load, and scoring means that the pooled estimate represents an average across tasks rather than a uniform benefit across all working-memory measures.

The lack of a consistent benefit for cognitive flexibility may reflect its prolonged development and greater task specificity. Task switching requires inhibition of the previous task set, maintenance and updating of new rules, and reconfiguration of stimulus–response mappings, thereby integrating multiple control processes [1, 10, 67–69]. Performance also depends on rule comprehension, goals, and prior experience [70]. A single CEPA bout may facilitate relatively direct inhibitory and updating processes without being sufficient to improve integrated switching performance. Repeated switching practice may be required for near transfer, whereas excessive cognitive demands may create competition for limited resources [14, 29]. The nonsignificant pooled effect should therefore not be interpreted as evidence that acute CEPA is ineffective for cognitive flexibility; developmental level, task alignment, and load balance may determine whether benefits emerge.

4.3 Patterns of effects across exercise modalities

Both non-digital CEPA and exergaming were associated with better inhibitory control, suggesting that digital technology may not be necessary for this benefit. Repeated engagement in goal maintenance, response selection, and behavioral monitoring may be more important [20–22, 63]. Exergaming can provide continuous audiovisual cues, immediate feedback, and adaptive difficulty, but games vary in physical demands, feedback design, and cognitive load [71, 72]. Previous syntheses also indicate that skill learning, cognitive challenge, and implementation context influence cognitive outcomes [73]. Digital devices may therefore serve primarily as delivery platforms rather than independent active components.

The different patterns for working memory and cognitive flexibility may reflect process alignment. Non-digital CEPA often requires children to maintain multiple rules and update their actions using spatial, sequential, and social information, thereby engaging working memory. Exergaming typically requires rapid attentional shifts and repeated adjustment of stimulus–response mappings, which more closely resembles task switching. Process-specificity and near-transfer accounts predict greater benefits for cognitive processes repeatedly engaged during an activity [14, 63–65], and previous acute exergaming studies provide indirect support for this explanation [25, 49].

Current evidence does not establish the superiority of either modality. Without formal between-subgroup tests, significance in one subgroup but not another does not demonstrate a difference between modalities [74]. Future studies should directly compare modalities while matching intensity and duration and should quantify rule load, feedback density, decision-making demands, and task-switching frequency to identify the active components.

4.4 Patterns of effects across exercise intensities

Within-subgroup estimates indicated improved inhibitory control at both low and moderate intensities, suggesting that a high physiological load may not be necessary for this outcome. Even low-intensity CEPA repeatedly engages inhibitory processes through rule monitoring, response selection, and suppression of prepotent responses, whereas moderate-intensity CEPA may additionally increase arousal and attentional recruitment [21, 22, 59]. Thus, physical and cognitive loads may jointly shape intervention effects, and exercise intensity alone may be an incomplete measure of intervention dose.

The patterns for working memory and cognitive flexibility may reflect different demands on physiological arousal and task-specific stimulation. The significant estimate for working memory in the moderate-intensity subgroup may reflect the effects of moderate arousal and catecholaminergic modulation on information maintenance and updating [17, 62]. However, prefrontal control may decline when catecholaminergic or stress-related signaling exceeds an optimal range [75]. Previous meta-analytic evidence also suggests that responses to acute moderate-intensity aerobic exercise vary by age, physical fitness, and executive function component [76]. Cognitive flexibility may depend more on explicit and repeated switching demands. Increasing physical load without such demands is unlikely to promote near transfer, whereas excessive combined physical and cognitive loads may create competition for limited resources [29, 60].

These findings do not establish that higher-intensity CEPA is more effective. Because high-intensity comparisons were limited and formal between-subgroup tests were not conducted, neither the optimal intensity nor an inverted-U relationship can be established [35, 61, 74]. Future factorial studies should independently manipulate and objectively monitor physical intensity and cognitive load.

4.5 Patterns of effects across session durations

Because session durations varied little for working memory and cognitive flexibility, duration-based subgroup analysis was restricted to inhibitory control. Positive within-subgroup estimates were observed for sessions lasting > 15 min, whereas the estimate for shorter sessions was imprecise. Duration may influence both postexercise arousal and the opportunities to practise rule monitoring, response selection, and response inhibition [35, 58, 59, 77]. Short sessions may provide insufficient cognitive stimulation, whereas additional time may allow repeated recruitment of the targeted processes. The inhibitory-control benefit reported after a 20-min CEPA session in children is consistent with this interpretation [45].

However, these findings do not establish a linear duration–response relationship. Longer sessions may provide more task-specific practice but may also increase fatigue, attentional decline, and cumulative load. These competing effects likely depend on the alignment among exercise intensity, cognitive demands, and children's capabilities [60, 77]. Given the unequal subgroup sizes and the absence of direct comparisons and formal between-subgroup tests, the 15-min cutoff should not be interpreted as a minimum effective threshold, and the optimal duration remains unknown [74]. Future studies should

directly manipulate session duration while holding other activity characteristics constant and assess outcomes at multiple postexercise time points.

4.6 Patterns of effects across age groups

Age-stratified estimates suggested component-specific rather than uniformly greater benefits with increasing age. Executive function components follow distinct developmental trajectories throughout childhood [10, 36, 67–69], as do attentional control, response inhibition, and working memory [78, 79]. Positive within-subgroup estimates emerged for working memory in younger samples (< 8 years) and for inhibitory control and cognitive flexibility in older samples (≥ 8 years). Although developmentally plausible, these patterns do not establish that age moderates the effects of acute CEPA.

Working memory capacity and updating develop rapidly in younger children. Rule maintenance, movement-sequence retention, and feedback-based updating during CEPA may repeatedly engage these processes, while lower baseline capacity may leave greater room for improvement. Older children may be better able to maintain goals, process multiple rules, and adjust strategies, facilitating the transfer of embedded inhibition and switching practice to outcome tasks. Conversely, complex rules and frequent switching may exceed younger children's executive resources [1, 14, 70]. The observed patterns may therefore reflect alignment between developmental capacity and task demands rather than an independent effect of chronological age.

Study samples were classified using mean age. These study-level patterns may therefore be confounded by activity modality, task difficulty, baseline ability, and outcome measurement and should not be interpreted as individual-level age effects. The 8-year cutoff was exploratory and does not represent a biological boundary. Future studies should compare age groups within the same study, report age and baseline executive function at the individual level, and use CEPA protocols with adaptive difficulty to test whether effects depend on the alignment between developmental capacity and task demands.

4.7 Strengths and limitations

This review has several strengths. By focusing on the immediate effects of a single bout of CEPA in healthy children aged 4–12 years, it avoided conflating acute and longer-term interventions and improved the directness of the evidence. It included randomized parallel-group and cluster trials, together with crossover or within-participant trials with randomized condition order. Prospective protocol registration, searches of multiple databases and reference lists, and independent duplicate study selection, data extraction, risk-of-bias assessment, and certainty-of-evidence assessment strengthened methodological rigor. Separate analyses of overall executive function and its three core components, together with exploratory analyses by activity modality, exercise intensity, session duration, and age group, provided a more detailed characterization of the observed effects.

Several limitations warrant consideration. First, the number of included studies was small, subgroup sizes were uneven, and no formal between-subgroup tests were conducted. Differences in significance between subgroups therefore do not establish moderation. Evidence for high-intensity CEPA was limited,

and duration-based analyses were restricted to inhibitory control. Second, control conditions ranged from no exercise to physical activity with low cognitive engagement. The pooled estimates therefore represent average effects across heterogeneous comparisons and cannot isolate the respective contributions of physical load and cognitive engagement. Third, differences in activity content, cognitive load, intensity assessment, and executive function tasks limited comparability across studies. Most studies also lacked standardized, objective measures of cognitive engagement. Fourth, most studies raised some concerns regarding risk of bias, and the evidence for cognitive flexibility was heterogeneous and of low certainty. Finally, only immediate postexercise effects in healthy children were examined; the persistence of these effects and their generalizability to clinical or developmental populations and longer-term interventions remain unknown.

Future studies should use standardized, quantifiable CEPA protocols and active controls matched for physical load. Direct comparisons of intervention parameters, formal between-subgroup tests, individual participant data analyses, and delayed follow-up assessments would improve the interpretability and practical relevance of the evidence.

5. Conclusions

Acute CEPA may produce small immediate improvements in executive function in children aged 4–12 years, with more consistent evidence for inhibitory control and working memory than for cognitive flexibility. Exploratory subgroup findings suggest that effects may vary by activity modality, exercise intensity, session duration, and age group. Direct comparisons and formal between-subgroup tests are needed before these factors can be considered moderators.

Abbreviations

ACSM American College of Sports Medicine

ADHD Attention-deficit/hyperactivity disorder

CEPA Cognitively engaging physical activity

CI Confidence interval

CNKI China National Knowledge Infrastructure

EFs Executive functions

GRADE Grading of Recommendations Assessment, Development and Evaluation

HRmax Maximal heart rate

M Mean

PERSiST Implementing PRISMA in Exercise, Rehabilitation, Sport Medicine and Sports Science

PICOS Population, Intervention, Comparison, Outcomes, and Study design

PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PRISMA-S Preferred Reporting Items for Systematic Reviews and Meta-Analyses literature search extension

PROSPERO International Prospective Register of Systematic Reviews

RoB 2 Version 2 of the Cochrane risk-of-bias tool for randomized trials

SD Standard deviation

SMD Standardized mean difference

Declarations

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Availability of Data and Materials

All the data generated from the analyses in this study are provided in the Supplemental Material.

Competing Interests

The authors declare that they have no competing interests.

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Not applicable.

Authors' Contributions

Pengyu Wang: Methodology, Resources, Software, Writing – original draft, Writing – review & editing. Tolegenuly Nurzhan: Conceptualization, Supervision, Validation, Writing – review & editing.

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Figures

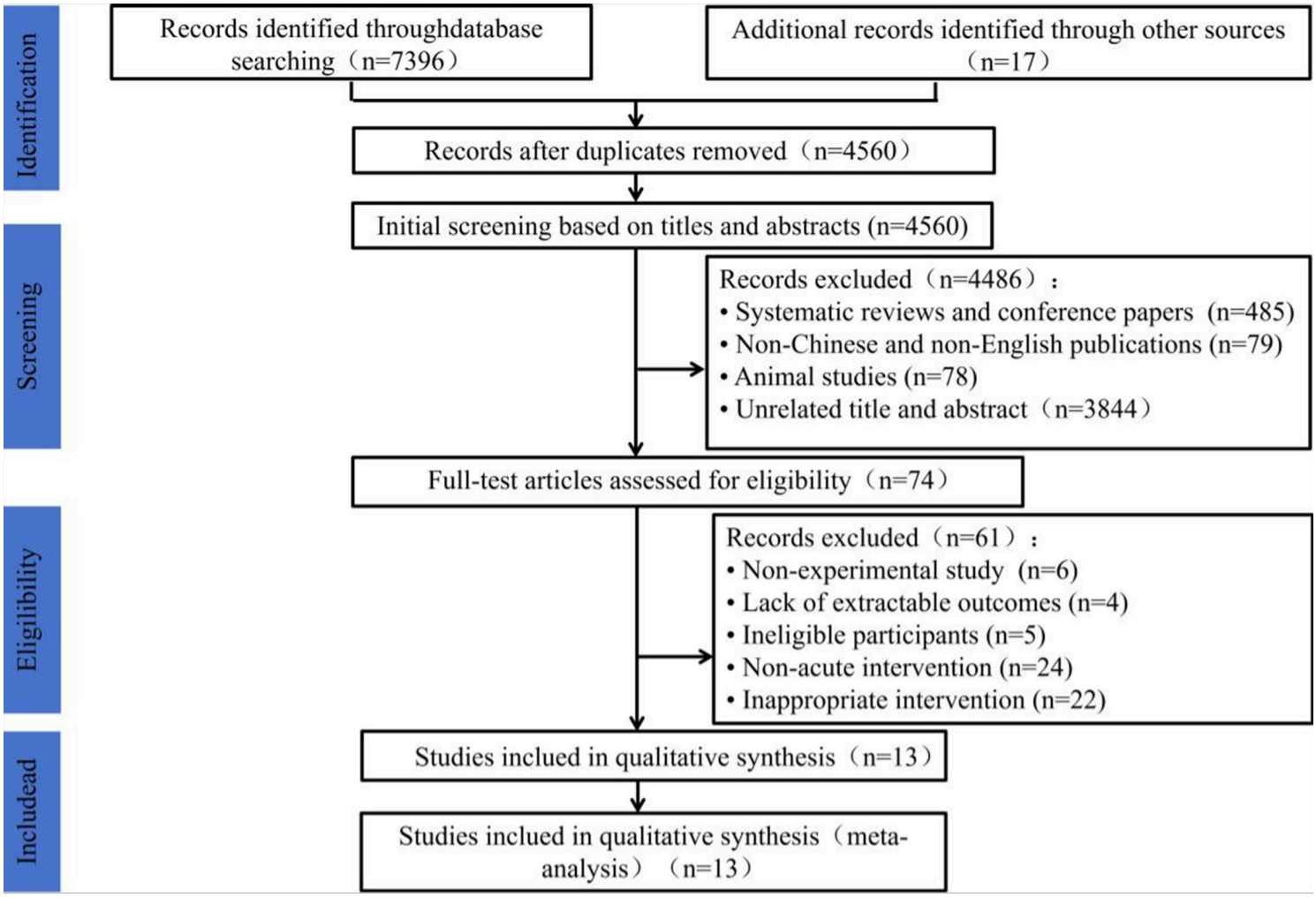


Figure 1

Flowchart of the screening process

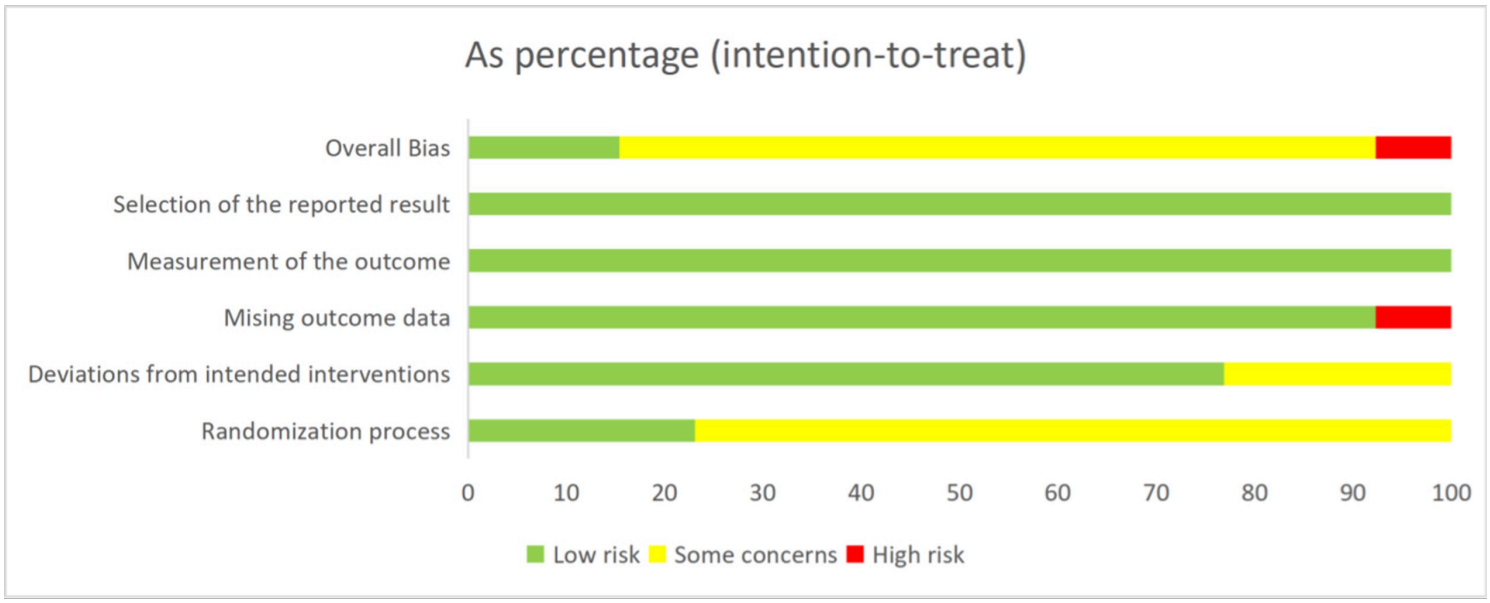


Figure 2

Summary of the risk in the included RCTs

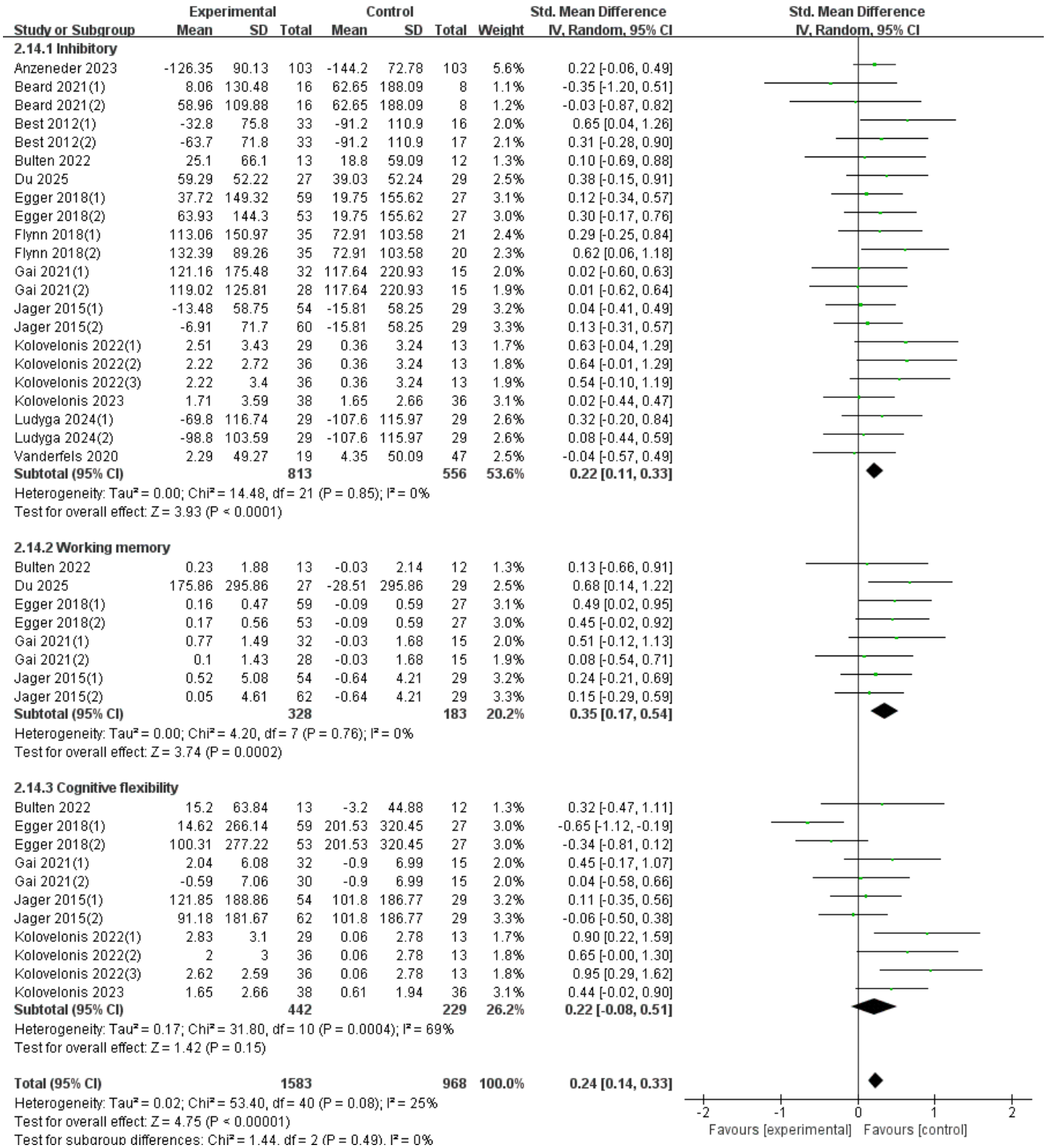


Figure 3

Forest plot of the impact of Cognitively Engaging physical exercise on executive functions

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