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Research article

Effects of aerobic exercise on children's executive function and academic performance: A systematic review and meta-analysis

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ABSTRACT

Objective: To investigate the effects of exercise on executive function in children, providing an evidence-based foundation to inform future research in school physical education and health education.
Methods: We searched ten databases: Cochrane Library, Scopus, OVID, Web of Science, PubMed, EBSCOhost, SPORTDiscus, PsycINFO, CNKI, WANFANG DATA, VIP, and SinoMed, and eight articles were included. Applying the revised Cochrane Risk of Bias Tool for Randomized Trials (RoB2), funnel plots and Egger regression analysis were integrated with R meta-analysis to screen for publication bias. The quality of the evidence was appraised using the Grading system.
Results: The included literature contained 2655 participants, with 1308 in the experimental group and 1347 in the control group. The results indicated that the aerobic exercise group considerably improved inhibitory control in children compared to the control group [SMD = 0.29, 95% CI (0.05, 0.54), $P = 0.018$]; working memory [SMD = 0.25, 95% CI (0.07, 0.42), $P = 0.005$]; and cognitive flexibility [SMD = 0.36, 95% CI (0.17, 0.54), $P < 0.001$]. However, the findings indicated that only aerobic exercise interventions extending beyond 50 weeks positively influenced academic performance in children [SMD = 1.19, 95% CI (0.34, 2.04), $P = 0.006$]. The results of an Egger regression analysis revealed that the p-values for inhibitory control, working memory, cognitive flexibility, and academic performance were more significant than 0.1. The Grade system said that the quality of evidence was all low regarding the level of evidence.
Conclusion: Aerobic exercise enhanced executive function but only aerobic exercise interventions extending beyond 50 weeks demonstrated a significant effect on the academic performance of children. Due to the low quality of evidence presented in this study, additional high-quality randomized controlled trials are needed to confirm these findings.

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Key Points

1. Aerobic exercise significantly enhances children's executive functions, including inhibitory control and working memory.
2. Aerobic exercise interventions exceeding 50 weeks significantly impact children's academic performance.
3. The long-term benefits of aerobic exercise highlight the importance of sustained interventions.

1. Introduction

Physical activity (PA)'s influence on psychological functions, especially cognitive functions (CF), has attracted much research interest. Executive function (EF), a key element of CF, also known as "executive control" or "cognitive control," involves mental processes that enable individuals to override automatic responses and focus attention [1]. EF is crucial for managing thoughts, emotions, and actions. It aids cognitive and socio-psychological development, enhancing success in academics and daily life [2]. It's noteworthy that the ages of 6–11 represent a critical period for the development of EF in children. Typically, by the age of 10, the progression of this function begins to stabilize, gradually approaching adult levels [2].

PA, also referred to as exertional activity, encompasses any activity resulting in energy expenditure due to skeletal muscle contractions. This includes tasks within daily life such as work, domestic chores, sports exercises, and recreational activities [3]. The benefits of PA on physical fitness and mental health are well investigated by various research [4]. It is critical in preventing and treating illnesses and disorders with a wide range of origins.

Studies show that various physical activities can reduce adults' risk of chronic diseases such as obesity [5,6], cardiovascular diseases [7,8], diabetes [9]; and improve mental and neurological disorders including [10], depression [11], and Parkinson disease [12].These findings underscore the extensive and profound impact of PA in the prevention and treatment of diseases across a spectrum ranging from psychological to neurological dimensions. Additionally, recent research has suggested that physical exercise benefits the development of different areas of the neurological and psychological function of children [13–15] and improves CF and EF, such as attention, memory, learning, and problem-solving [16]. Specifically, aerobic exercise (AE) exhibits significant impact on EF at the level of brain mechanisms. This is primarily manifested by increased activity in the bilateral prefrontal cortex and decreased activity in the bilateral parietal lobe. Accompanying these changes is the remodeling of white matter integrity and an enhancement in the overall efficiency of neural circuits in the brain [17,18]. Brain imaging studies have revealed that regular PA considerably impacts higher cognitive processes and the functional connections of associated brain areas while enhancing motor performance, which is an important strategy to boost brain development and learning in children [19–21].

While we recognize the positive effects of physical exercise on various neurocognitive and psychological domains in children, research remains inconclusive regarding the specifics of how and to what extent AE influences their EF and academic performance (AP) [22,23]. Given the pivotal role of EF in the development of children and the widespread application of AE, a deeper exploration of this topic is paramount. Therefore, employing a meta-analytic approach, this study aims to systematically assess the direct impacts of children's EF and AP. Through this research, we aspire to offer more precise and actionable recommendations for future physical exercise planning for children, as well as insights for subsequent studies.

2. Methodology

The systematic review and meta-analysis were carried out and presented in accordance with PRISMA standards, please refer to Supplementary Appendix A for further details, and the registration number in PROSPERO is CRD42023414191.

2.1. Literature search

We conducted a comprehensive search of ten databases (Cochrane Library, Scopus, OVID, Web of Science, PubMed, EBSCOhost, SPORTDiscus, PsycINFO, CNKI, WANFANG DATA, VIP and SinoMed) related to health, medicine, sport, and exercise up to November 13, 2023 to explore the effects of AE on CF and EF in children. In addition, we included relevant previous studies. We used the following search terms: ("PE" or "physical education" or "exercise" or "physical activity" or "aerobic exercise" or "walking") and ("memory" or "cognitive control" or "academic behavior" or "academic performance" or "school performance" or "cognitive flexibility") (see Supplementary Appendix B for details). Two authors independently assessed the references for inclusion and exclusion criteria and screened the subject-related meta-analysis literature to ensure no potentially relevant articles were missed.

2.2. Criteria of inclusion and exclusion

Studies were included if they met the following criteria:

(1) Type of Research: Randomized controlled trials (RCTs). (2) Subjects: Healthy children. (3) Intervention: Any AE (excluding studies exploring immediate effects of exercise). (4) Outcomes Measured: Inhibition control, cognitive flexibility, working memory, and AP. (5) Language: Articles published in either English or Chinese.

Studies were excluded based on the following criteria:

(1) Duplicates: Studies that were repetitive or duplicate entries. (2) Publication Type: Unofficially published articles, pre-printed articles, or articles without peer review. (3) Article Type: Reviews, case reports, or other non-original research. (4) Availability: Unavailability of the full-text of the article. (5) Outcome Clarity: Studies where outcome indicators did not meet the requirements or lacked clear, defined outcomes.

2.3. *Trials quality assessment*

The quality of the literature was assessed using the Revised Cochrane Risk of Bias Tool for Randomized Trials (RoB2). The RoB2 tool is widely used to evaluate the risk of bias in randomized trials. It assesses the quality of the trial across five domains: (1) Randomization process, (2) Deviations from the intended interventions, (3) Missing data outcome data, (4) Measurement of the outcome, and (5) Selective of the reported result. Each domain is evaluated using a series of signaling questions, with the overall risk of bias being judged as low, some concerns, or high, based on the responses to these questions.

2.4. *Statistical analysis*

We primarily extracted two mathematical indicators from the AE and control groups: the means and standard deviations (SD) of the pre- and post-intervention. As the extracted data are continuous variables, we used a 95% confidence interval (CI) in line with previous research [24]. The analysis statistics were primarily expressed in terms of mean differences (MD) [25]. Specifically, it computes the discrepancy between the mean values of two independent samples, elucidating the quantitative difference between the effects of the intervention and the control. To minimize bias in our meta-analysis, we initially analyzed heterogeneity. We applied the following rule: (1) when $P > 0.1$ and $I^2 \leq 50\%$, heterogeneity was considered not significant and could be combined using a fixed effects model. I^2 represents the ratio of between-study variance to the total variance (intra-study variance plus between-study variance); (2) when $P < 0.1$ and $I^2 > 50\%$, heterogeneity was considered large, and a determination of the source of heterogeneity was required. If no reason for the significant heterogeneity was identified, a random effects model was used for combination. (3) If the heterogeneity was too great or the data source was unavailable, we used descriptive analyses. All data evaluations were carried out using the meta-package in R (version 4.1.3). If more than ten studies were included for a single outcome measure, publication discrepancies were assessed using funnel plots and Egger's test. If fewer than ten studies were included for a single outcome measure, we only used Egger's test to assess publication bias.

2.5. *Assessment of results using the GRADE approach*

The Grading of Recommendations Assessment, Development, and Evaluation, evaluates research based on five distinct criteria,

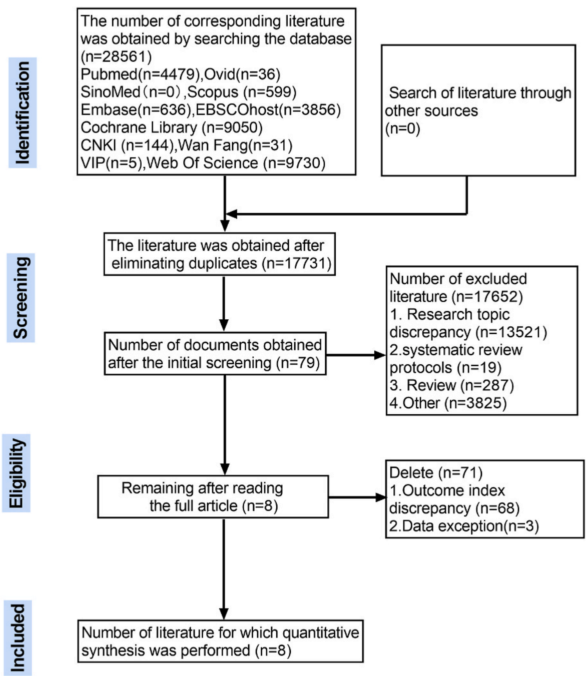

Fig. 1. PRISMA flow diagram illustrating the study selection process for this systematic review and meta-analysis.

Table 1
Initial attributes of the selected studies.

Study	County	Group (n)	Age (years)	Conditions of Participation	Interventions	Location	Outcomes
Gall2018	South Africa	265	9.28 (9.20–9.36)	Between 8 and 13years of age. Complete reporting to three data: variable concentration performance, error percentage, and year-end results.	Includes four components: regular physical activity classes, moving to music, regular recess, and physical activity with the school's existing conditions.The exercise lasted 20 weeks, 5 times a week.	School	④
		398	9.22 (9.14–9.29)		Perform regular physical activities without additional physical work related content.		
Hillman 2014	USA	109	8.8 (8.7–8.9)	Between 7 and 17 years of age. More than half of the participants in both groups were white, and more than 40% were categorized as low socioeconomic status.	Participants ran/walked at a constant speed on a motorized treadmill in 2-min increments until volitional fatigue.The exercise lasted for 9 months, 120 min each time, 5 times a week, with moderate to vigorous intensity.	School	① ②
		112	8.8a (8.7–8.9)		Perform regular physical activities without additional physical work related content.		
Kamijo 2011	USA	20	8.9 (0.5)	Between 7 and 9 years of age.; They have no neurological disorders or physical disabilities and have (corrected) normal vision.	Combined sports that require high aerobic capacity such as dribbling. The exercise lasted for 9 months, 120 min each time, 5 times a week, with moderate to vigorous intensity.	School	②
		16	9.1 (0.6)		Perform regular physical activities without additional physical work related content.		
Moreau 2017	New Zealand	152	9.87 (1.81)	The age range of participants spanned from 7 to 9 years. None had a documented instance of traumatic brain injuries or epilepsy, and all had either inherent or corrected-to-normal vision.	Participants underwent a rigorous aerobic regimen for a duration of 12 weeks. Sessions were held thrice weekly, lasting 40 min each, operating at about 85% of an individual's peak heart rate.	School	① ③
		153	9.96 (1.68)		Perform regular physical activities without additional physical work related content.		
Niet2016	Netherlands	47	8.8 (0.8)	Children in the study ranged from 8 to 12 years old. A notable majority, accounting for 82%, shared a consistent socioeconomic status (SES), determined primarily by their parents' educational levels.	Engagements involved various athletic drills, featuring tasks like circuit-based exercises. This includes but is not limited to activities like sit-ups, push-ups, and skipping rope. Exercise for 10 weeks, 30 min each time, 5 times a week, at moderate to high intensity.	School	② ③
		52	8.9 (1.2)		Perform regular physical activities without additional physical work related content.		
Veldman 2020	Australia	30	7.62 (1.83)	The study encompassed participants ranging from 8 to 12 years old. Those diagnosed with medical conditions, such as cerebral palsy, that might impede physical activities were not included.	Each engagement incorporated a rotational team sport, alternating among games like soccer, netball, basketball, and touchdown/Oztag. On special occasions, sessions were themed after renowned television shows such as The Amazing Race and Survivor. Exercise for 20 weeks, 60 min each time, 3 times a week, at moderate to high intensity	School	① ② ③
		30	7.84 (1.87)		Perform regular physical activities without additional physical work related content.		
Butzer 2015	USA	44	–	Among students in grades 9–12, 91% were white, followed by 3.8% Hispanic, 3% other multiracial, 1.7% African American, and 0.5% Asian.	Yoga Classes.Exercise lasts 12 weeks, 35–40 min each time, 2–3 times a week.	School	④

(continued on next page)

Table 1 (*continued*)

Study	County	Group (n)	Age (years)	Conditions of Participation	Interventions	Location	Outcomes
		51	–		Perform regular physical activities without additional physical work related content.		
Ahamed 2007	Canada	214	10.2 (0.6)	Healthy and from multiple geographies	Exercise for 12 weeks, 35–40 min per session, 2–3 times per week, at moderate to high intensity.	School	④
		74	10.2 (0.6)		Perform regular physical activities without additional physical work related content.		
Gao 2013	America	85	10.32 (0.91)	(1) Aged 10–12 years; (2) From Hispanic families; (3) No physical or mental disabilities diagnosed.	Three 30-min sessions per week of video game-based exercise (DDR, aerobic dance).	School	④
		123	10.28 (0.90)		The control group intervention involved no structured exercise program, only participation in regular, unorganized recess activities like sitting, walking, or playing on the playground.		
Telford 2012	Australian	312	8–10	The racial ancestry of the children (either from one or both parents) was as follows: 86% Caucasian, 8% Asian, 3% Aboriginal Australian or Torres Strait Islander, 1% Polynesian, with 2% of the data missing.	Physical education was conducted under the guidance of professional PE teachers for 150 min weekly	School	④
		308			With regular activities led by the class teacher		
Shen2020	China	30	4.37 (0.33)	Healthy and normally developing preschool children with no prior similar dance training experience	An 8-week street dance training program was conducted, consisting of 3 sessions per week, each lasting 40–50 min, totaling 24 sessions.	School	① ② ③
		30	4.64 (0.35)		The control group did not participate in any training and only engaged in regular kindergarten activities.		

–: not mentioned in the literature; ①inhibition control; ②cognitive flexibility; ③working memory; ④Academic performance.

These include: (1) risk of study bias, (2) publication bias, (3) indirectness, (4) imprecision, and (5) inconsistency [26]. Each subdomain assigns a grading of four levels of high, medium, low, and very low based on different qualities of trials. The two authors simultaneously evaluated the quality of the trials based on the two instruments. In the event of unresolved disagreements between the two authors regarding the quality assessment of a study, a third author was consulted to make a final determination.

3. Outcomes

Following the inclusion and exclusion criteria, we selected relevant articles by reviewing titles and abstracts, focusing on those related to AE and children's CF and EF, and then examined the full texts. As a result, eight eligible articles were obtained (see details in Fig. 1).

3.1. Initial attributes of the selected studies

The meta-analysis incorporated data from eight distinct trials, involving 1767 children aged 6–12 years. Most of these studies were conducted after 2010, except for one from 2007. The trials were conducted in various developed countries, with one in South Africa, a developing country. All interventions were conducted within school settings. Exercise intensities varied, mostly ranging from moderate to strenuous. Intervention durations varied, ranging from as long as 36 weeks to as short as 10 weeks. Individual sessions in these programs lasted 20–120 min, occurring 2 to 5 times weekly. The primary outcomes of interest across these trials were inhibitory control, cognitive flexibility, working memory, and AP. A comprehensive breakdown of each study's characteristics is available in Table 1.

3.2. Quality assessment of included literatures

Upon reviewing the included studies, "Deviations from Intended Interventions" was identified as an areas of concern. All fourteen studies exhibited "some concerns" in these section. This is primarily attributed to the inherent characteristics of exercise interventions, where the precise implementation of blinding methods presents significant challenges. Due to the active and participatory nature of exercise regimes, it becomes difficult to maintain blinding for participants and personnel. In the domains of "Missing Outcome Data" and "Measurement of the Outcome," one study presented "some concerns." Additionally, two studies raised "some concerns" in the "Selection of the Reported Result" section. It is reassuring to note that none of the studies were categorized as "High Risk." Detailed information is shown in Fig. 2A. Summarily, all the included studies were classified as having "some concerns" in the overall assessment. A detailed breakdown is available in Fig. 2B.

3.3. *Inhibitory control*

One of the variables receiving significant attention in the included research was inhibitory control capacity. Inhibitory control, a main component of EF, refers to the ability to suppress intrusive responses and attentional tendencies in order to complete a task. This review evaluated the impact of AE on children's inhibitory control by analyzing four studies [22,27–29]. The findings demonstrated between-study heterogeneity ($P = 0.100$, $I^2 = 52.0\%$) in the four trials. Using a random effects model, we identified a significant distinction between the AE cohort and the traditional control set [SMD = 0.29, 95% CI (0.05, 0.54), $P = 0.018$]. Further details can be found in Fig. 3A. This strongly suggests that children who engaged in AE had better inhibitory control performance compared to those who did not engage as much in AE. Due to the limited number of included articles, only Egger's test was used to assess ($p = 0.4411$) (see Fig. 4A for details).

3.4. *Working memory*

Working memory is another prominent indicator used to assess EF. Working memory refers to short-term systems for processing and storing data during higher-order cognitive tasks such as memory, reasoning, and problem-solving. This research investigated the impact of persistent AE on children's working memory by analyzing the results of four trials [22,29–31]. We first examined the heterogeneity of the four included studies. The findings indicated that there was no significant heterogeneity among the included studies. ($P = 0.836$, $I^2 = 0.0\%$), therefore, a fixed effects model was adopted for the analysis, which revealed a statistically significant difference between the AE group and the conventional control group [SMD = 0.25, 95% CI (0.07, 0.42), $P = 0.005$] (see Fig. 3B for details), indicating a significant increase in working memory performance due to AE. Due to the insufficient number of included articles, only Egger's test was employed to assess publication bias and the findings indicated significant publication bias ($p = 0.4482$) (see Fig. 4B for details).

3.5. *Cognitive flexibility*

Cognitive flexibility is another key indicator used to assess EF. Cognitive flexibility refers to the ability to switch between different mental processes to generate appropriate behavioral reactions. This study examined the impact of prolonged AE on children's cognitive flexibility by analyzing five trials [22,28–30,32]. Additionally, the heterogeneity among the included studies was minimal (*P*

Fig. 2. A: Methodological quality distribution of the included 14 RCTs; B: Bias risk graph and summary for the included 14 RCTs.

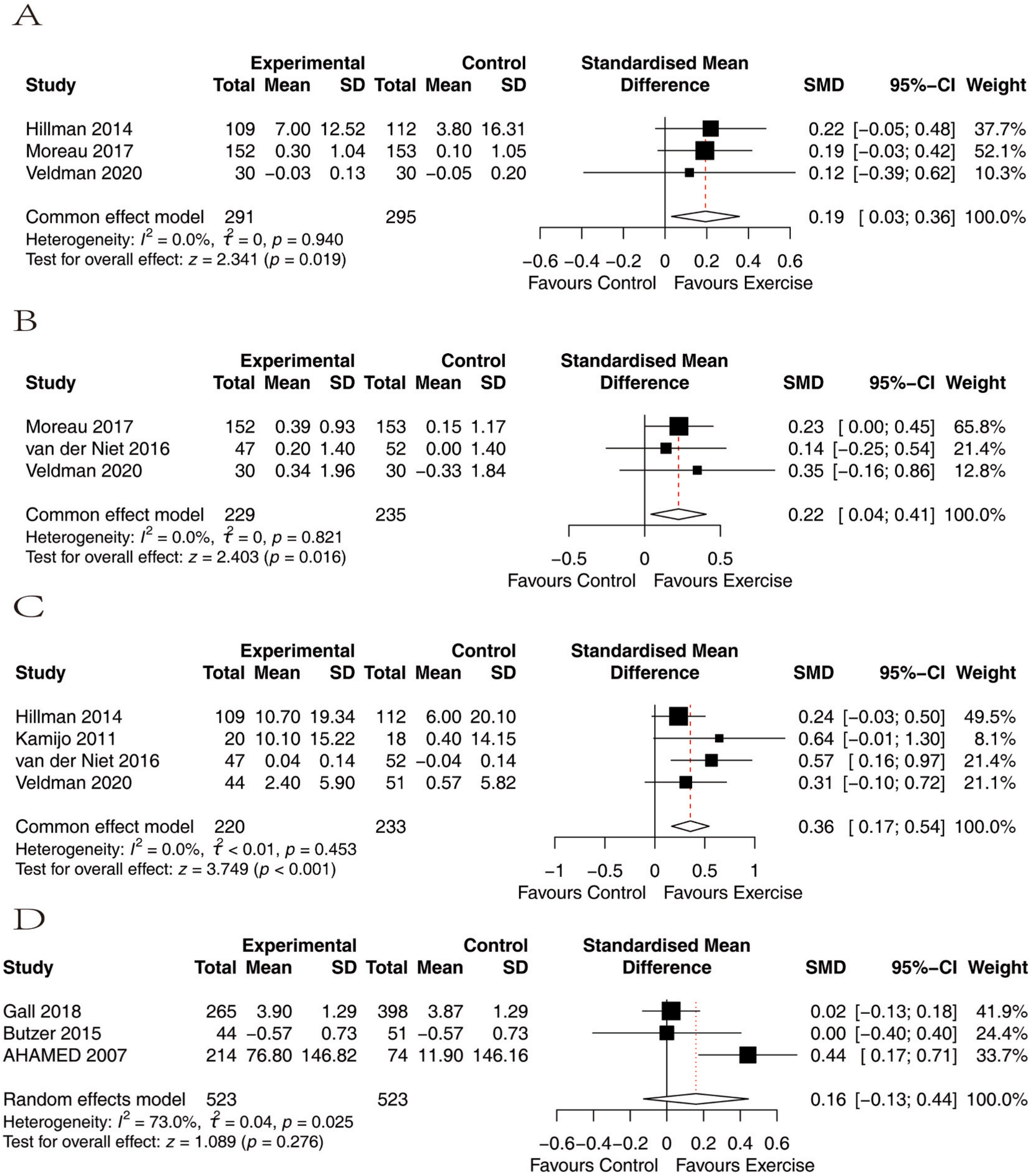

Fig. 3. Meta-analysis outcomes: effect sizes and statistical significance for A) inhibitory control, B) working memory, C) cognitive flexibility, and D) academic performance.

$= 0.563$, $I^2 = 0.0\%$). Using the fixed effects model, a marked difference emerged between the AE participants and the designated control group [SMD = 0.34, 95% CI (0.16, 0.51), $P < 0.001$] (see Fig. 3C for details). This indicates that sustained AE significantly enhances children's cognitive flexibility. Due to the limited number of included articles, only Egger's test was used to assess publication bias, and the findings indicated no significant publication bias ($p = 0.3396$) (see Fig. 4C for details).

3.6. AP

In addition to the usual indications used to EF, AP is a standard indicator for assessing academic improvement in children. AP typically refers to a student's AP, evaluated through classroom performance, graduation rates, and standardized test results. This study analyzed four publications to assess the effect of AE on children's AP, and heterogeneity analysis revealed substantial differences among the five included studies [23,33–36] ($p < 0.001$, $I^2 = 97.8\%$). Consequently, a random effects model was applied. This analysis indicated no significant difference between the AE participants and the designated control set [SMD = 0.57, 95% CI (−0.02, 1.16), $P = 0.058$]. In the subgroup analysis, interventions lasting less than 50 weeks showed no significant effect on AP [SMD = 0.16, 95% CI

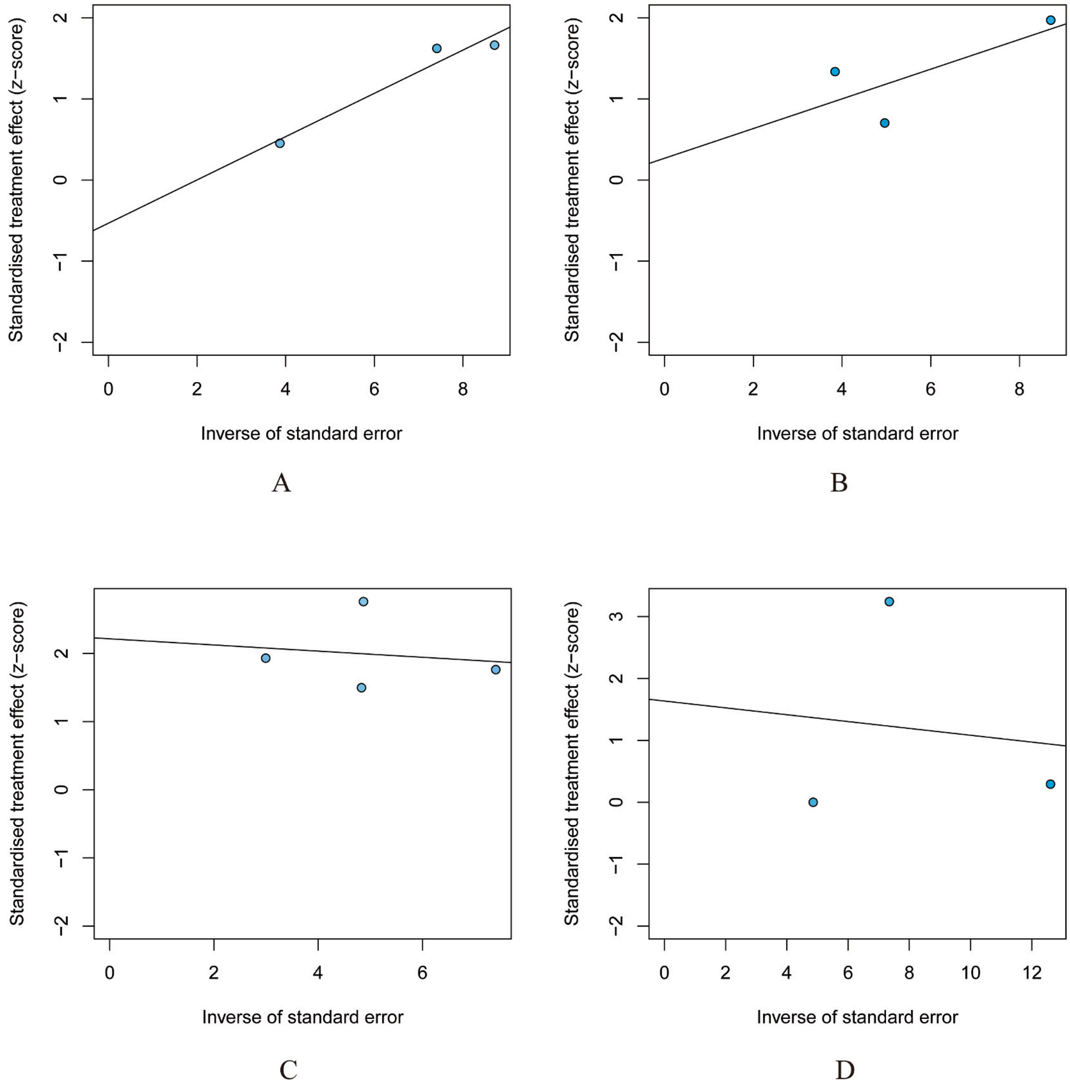

Fig. 4. Publication bias assessment results: egger regression analysis for A) inhibitory control, B) working memory, C) cognitive flexibility, and D) academic performance.

(−0.13, 0.44), $P = 0.276$]. In contrast, interventions of 50 weeks or longer demonstrated a significant improvement [SMD = 1.19, 95% CI (0.34, 2.04), $P = 0.006$] (see Fig. 3D for details). Due to the limited number of included articles, only Egger's test was used to assess publication bias and the findings indicated no significant publication bias ($p = 0.9387$) (see Fig. 4D for details).

3.7. GRADE evidence of outcomes

The GRADE assessment revealed that the four outcomes included in this systematic review were of low quality (see Table 2 for details). This might be because the featured studies' experimental procedures lacked randomization techniques, secret allocation sequences, or blinded evaluations. Additionally, the insufficient sample sizes in the included studies might have led to imprecise conclusions or weak evidence.

4. Discussion

4.1. Potential mechanism of AE

EF are fundamental to children's cognitive, emotional, and social maturation, with childhood being a pivotal phase for both cerebral cortex and EF development [37]. Sports Psychology Theory suggests that PA promotes cognitive growth by activating the bilateral prefrontal cortex of the brain [38,39]. Additionally, Arousal Theory posits that such activities amplify neurotransmitter

Table 2
Application of the GRADE criteria to aggregate findings in school-age children post extended aerobic exercise.

Outcomes	Illustrative comparative risks[c] (95% CI)	Number of participants (studies)	Certainty of the evidence
	Corresponding risk With exercise		
Inhibition control	The standard mean inhibition control in the exercise was 0.29 higher compared to usual care (0.05 lower to 0.54 higher)	646 (4 studies)	Low[a b]
Cognitive flexibility	The standard mean cognitive flexibility in the exercise was 0.34 higher compared to usual care (0.16 lower to 0.51 higher)	376 (5 studies)	Low[a b]
Working memory	The standard mean working memory in the exercise was 0.25 higher compared to usual care (0.07 lower to 0.42 higher)	523 (4 studies)	Low[a b]
Academic performance	The standard mean Academic performance in the exercise was 0.57 higher compared to usual care (−0.02 lower to 1.16 higher)	1874 (5 studies)	Low[a b]

High quality: Further studies are unlikely to alter our confidence in the effect estimate.
Moderate quality: Additional research may significantly impact our confidence and potentially change the effect estimate.
Low quality: Further studies are likely to greatly influence and likely change our confidence in the effect estimate.
Very low quality: Our confidence in the estimate is highly uncertain.
[a] Design limitations.
[b] Publication bias; ‡ imprecision; +heterogeneity.
[c] The term 'assumed risk' is defined as the median risk level observed within the control groups across the included studies, providing a baseline risk in the absence of any intervention. The resulting risk, presented alongside its 95% confidence interval, builds upon this assumption in conjunction with the observed relative effect of the intervention. Risk estimates were synthesized from pooled data of control groups. The determination of relative effect was informed by available case studies involving healthy children.

release in the prefrontal cortex, optimizing cognitive processes. Supporting these theories, animal studies indicate that exercise can: 1) bolster neurogenesis [40,41], 2) enhance angiogenesis [42], and 3) heighten synaptic plasticity [43,44], suggesting structural brain modifications that improve cognitive and motor learning capabilities. These insights emphasize the crucial role of exercise, especially during key developmental phases, and its recognition by the academic community as an enhancer of learning and cognition [45].

4.2. Outcome of this review

Building on prior research, this study focuses on AE's effects on children's EF, particularly on inhibitory control as shown in four studies. The results indicate that the AE group outperformed the control group in inhibitory control [SMD = 0.29, 95% CI (0.05, 0.54), P = 0.018]. And the analysis of the included studies also showed that children who did AE did statistically better in terms of both working memory [SMD = 0.29, 95% CI (0.05, 0.54), $P = 0.018$] and cognitive flexibility [SMD = 0.34, 95% CI (0.16, 0.51), $P < 0.001$]. These findings are consistent with prior research [45], which suggests that AE can considerably improve EF in children. In the meta-analysis conducted on inhibitory control, a moderate level of heterogeneity was observed ($P = 0.100$, $I^2 = 52.0\%$). Sensitivity analysis revealed a notable divergence in the findings of Shen's study compared to other included studies. Specifically, Shen's research demonstrated a significantly greater enhancement in inhibitory control following AE, in contrast to the more modest effects reported in other studies. A deeper examination of the literature revealed a critical distinction: Shen's study was the only one conducted among preschool children. This aligns with previous research suggesting that the impact of PA interventions is more pronounced in preschool children than in children [46]. This finding underscores the potential importance of early intervention in fostering cognitive development in children.

Although our comprehensive meta-analysis did not reveal a significant enhancement in AP among children due to AE, this study, through a more detailed subgroup analysis of the intervention duration, uncovered a more complex relationship pattern. Significantly, the positive effects of AE on AP became evident when the intervention period exceeded 50 weeks, highlighting the importance of prolonged intervention for academic enhancement. The absence of significant improvement in AP from short-term interventions may be attributed to various factors [47]. One reason could be the insufficient duration of AE to produce notable academic benefits [48]. Another is that the outcome measures used might need more objectivity and precision. Moreover, measuring academic achievement is inherently challenging, as it does not always directly correlate with EF [49]. For example, external factors like extracurricular tutoring and variations in intelligence distribution can significantly affect AP, complicating the assessment of exercise's impact on academic achievement [50]. Additionally, although subgroup analysis reduced inter-study heterogeneity, a moderate level remained, likely due to the use of various AP assessment methods. Our observations also indicated that most AE interventions for children are conducted in school settings. Such settings typically offer structured planning, wide student participation, advanced infrastructure, and ongoing supervision by professionals, thereby inherently promoting the development of social and collaborative skills [51]. Yet, a major limitation of these settings is the minimal parental involvement, which could be crucial in boosting the effectiveness of these interventions [52]. Conversely, out-of-school AE interventions, despite benefiting from greater parental involvement and enhanced parent-child interactions, frequently encounter challenges such as unsystematic planning, limited sports options, insufficient facilities, and a lack of professional guidance [53]. These limitations could impede the optimization of exercise outcomes.

Our evaluation of the four main outcome indicators using the GRADE assessment system revealed that the evidence level for each indicator is low. This indicates that while our study demonstrated a positive impact of AE on children's EF and AP, these findings must be interpreted cautiously due to the limited quality of evidence. Consequently, although our study offers valuable insights into the potential benefits of AE interventions for children's EF and academic achievements, additional high-quality research is needed to corroborate these results and diminish the current evidence's uncertainty. Future studies should aim to enhance study design quality, enlarge sample sizes, implement more stringent randomized controlled trial methods, and improve the objectivity and accuracy of outcome measurements to elevate the evidence level [54].

4.3. Study strengths and limitations

This study boasts several strengths, including: (1) Rigorous Methodology: We strictly adhered to established meta-analysis criteria, utilizing a wide array of databases such as the Cochrane Library, Scopus, OVID, Web of Science, PubMed, EBSCOhost, CNKI, WANFANG DATA, VIP, and SinoMed. This extensive search approach minimizes potential biases, thereby enhancing the robustness and precision of our findings. (2) Relevance of AE: The ubiquity of AE, which does not require specialized equipment, makes it widely accessible. Its frequent inclusion in children's routines highlights the practicality of our study, particularly in comparison to other forms of exercise.

Our study encountered several limitations: (1) Language and Geographic Restrictions: Our analysis was confined to English and Chinese language publications. This restriction might introduce geographic biases, thereby potentially limiting the global applicability of our findings. (2) Limited Depth in Cognitive Flexibility Analysis: Despite existing literature highlights significant developmental stages in cognitive flexibility, intricately linked to the maturation of the prefrontal cortex, our study was limited in its detailed exploration of these stages (notably at ages 7–9 and 11–13). This aspect was further limited by inadequate validation of moderating variables, like exercise type, frequency, and duration, which might contribute to heterogeneity in results. (3) Focus on Specific Exercise Intensities: A significant portion of the studies we included focused on moderate to vigorous exercise intensities, leaving a knowledge gap on the cognitive and academic ramifications of prolonged, low-intensity AE. (4) Use of Egger's Test: Considering the limited number of studies included, caution should be exercised in interpreting Egger's test for assessing publication bias. Despite these limitations, our study represents a significant step forward in providing an evidence-based foundation for future research in school physical education and health education.

5. Conclusion

Our research indicates significant improvements in inhibitory control, working memory, and cognitive flexibility in children following consistent AE, irrespective of duration. However, a notable finding is that significant enhancements in AP emerge only after engaging in AE for a period exceeding 50 weeks. This aligns with UNESCO's standards, highlighting the importance of quality physical education in promoting cognitive development and overall health in younger populations. While the evidence level for these findings is currently low, they represent an important initial exploration into the impact of PA on children's cognitive and academic abilities. Future research should aim to provide a more detailed understanding of the specific effects of AE on children's cognitive CF, executive skills, and academic outcomes, ensuring our educational approaches are both evidence-informed and holistic.

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Data availability statement

Data are available through corresponding authors.

CRediT authorship contribution statement

Wanli Zang: Writing – review & editing, Writing – original draft, Visualization, Validation, Data curation, Conceptualization. **Jinyi Zhu:** Writing – review & editing, Writing – original draft. **Ningkun Xiao:** Writing – review & editing, Writing – original draft. **Mingqing Fang:** Writing – review & editing, Writing – original draft. **Dong Li:** Writing – review & editing, Data curation, Conceptualization. **Haiming Li:** Writing – review & editing, Writing – original draft. **Jin Yan:** Writing – review & editing, Writing – original draft. **Hongying Jing:** Writing – review & editing, Writing – original draft, Visualization. **Su Wang:** Writing – review & editing, Writing – original draft, Visualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e28633.

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