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Mediators of the association between physical activity and executive functions in primary school children

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ABSTRACT

There is growing interest in identifying the mechanisms underpinning the effects of physical activity on executive functions (e.g. inhibitory control, cognitive flexibility) in children. Our study examined cardiorespiratory fitness, muscular fitness, and motor competence as potential mediators of this relationship. The study used baseline data from the Learning to Lead (L2L) cluster randomised controlled trial. In total, 675 children (7–11 years, 49.5% girls) completed measures of moderate-to-vigorous physical activity (MVPA), cardiorespiratory fitness, muscular fitness, motor competence, and executive functions. Structural equation modelling was used to examine the potential mediating roles of cardiorespiratory fitness, muscular fitness, and motor competence in the cross-sectional association between MVPA and executive functions. Cardiorespiratory fitness ($\beta = 0.06$, SE = 0.021, $p = 0.004$) partially mediated the association between MVPA and cognitive flexibility. Muscular fitness was a significant mediator of the association between MVPA and both inhibitory control ($\beta = 0.03$, SE = 0.014, $p = 0.027$) and cognitive flexibility ($\beta = 0.06$, SE = 0.021, $p = 0.005$). No significant mediated effects were found for motor competence. Our findings suggest cardiorespiratory and muscular fitness (but not motor competence) mediate the association between physical activity and executive functions in children.

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Moderate-to-vigorous physical activity; cardiorespiratory fitness; muscular fitness; motor competence; executive functions; children

Introduction

The health benefits of physical activity for young people are well documented and include a range of physical (e.g., enhanced physical fitness) and psychological (e.g., decreased depressive symptoms) benefits (Biddle et al., 2019; Chaput et al., 2020). There is also evidence that physical activity is beneficial for child and adolescent executive functioning (Biddle et al., 2019). Executive functions encompass the ability to select, schedule, coordinate, and monitor complex, goal-directed cognitive activities (Diamond, 2013). They include inhibitory control, which is the ability to maintain focus and suppress prepotent or automatised responses (such as avoiding distractions in the classroom), working memory, which is the ability to retain and update information when performing tasks (for instance, remembering multiple steps in solving a maths problem), and cognitive flexibility, which is the ability to shift mental resources between tasks (like when we need to adjust strategies in response to new rules in a game). Executive functions support higher-order processes such as problem solving, reasoning, and planning (Diamond, 2013; Willoughby & Hudson, 2023). In children, better executive functions are related to positive physical, psychological, and social-emotional health (Diamond, 2013; Riggs et al., 2006; Yang et al., 2022), whereas impaired executive functions may have detrimental effects on physical (e.g., a risk of obesity (Mamrot & Hanć, 2019)) and mental (e.g., depression (Gardiner & Iarocci, 2018; Hollocks et al., 2014)) health. Deficiencies in executive functions are also associated with suboptimal academic performance (Cortés Pascual et al., 2019; Jacob & Parkinson, 2015) and increased social-emotional challenges (e.g., poor social adaptation (Gardiner & Iarocci, 2018; Riggs et al., 2006)).

Previous studies have shown that, although the effects are typically small, physical activity interventions are generally beneficial to children and adolescents' executive functions (Ciria et al., 2023; García-Hermoso et al., 2021; Singh et al., 2019; Xue et al., 2019). Given that children spend a substantial amount of time at school, it is important to explore how physical activity during school hours contributes to these cognitive benefits. There is also growing acknowledgement of the importance of identifying the mechanisms responsible for the effect of physical activity on executive functions. A deeper understanding of these mechanisms may help to inform the design and implementation of future physical activity programmes. The existing evidence suggests that this relationship is likely influenced by both the qualitative (e.g., type, level of

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cognitive demand) and quantitative (e.g., intensity) characteristics of the physical activity (Best, 2010; Hill et al., 2023; D. R. Lubans et al., 2021; Willoughby & Hudson, 2023). However, there is no consensus on the relative contributions of these characteristics (Diamond & Ling, 2019; Hillman et al., 2019). Work in this area has resulted in the proposition of two related hypotheses: the "fitness" and the "skill acquisition" hypotheses (Petruzzello et al., 1997; Tomporowski & Pesce, 2019). The "fitness" hypothesis suggests that participation in physical activity of sufficient duration and intensity to improve fitness (e.g., cardiorespiratory fitness, muscular fitness) may enhance cognition via changes in the structure and function of the brain (Petruzzello et al., 1997; Tomporowski & Pesce, 2019). The "skill acquisition" hypothesis suggests that physical activity provides opportunities for skill acquisition, and subsequent improvements in cognition are driven by the influence of skill acquisition on changes to related neural pathways (Tomporowski & Pesce, 2019). More specifically, it is engagement in cognitive complex and/or novel movements that likely lead to improvements in executive functions.

There is evidence from cross-sectional and experimental studies in support of the "fitness" hypothesis. Reviews of the literature suggest that cardiorespiratory fitness is positively associated with executive functions in children and adolescents (Best, 2010; De Greeff et al., 2018; Hillman et al., 2008). Changes in executive functions may be attributable, at least in part, to exercise-induced increases in neurotrophins (including brain-derived neurotrophic factor and insulin-like growth factor) that subsequently influence brain structure and function (Khan & Hillman, 2014; Stillman et al., 2016). There is also evidence that changes in muscular fitness (i.e., muscle strength, endurance, and power) may provide some explanation for the relationship between physical activity and executive functions (Robinson et al., 2023; Soga et al., 2018). A recent meta-analysis found that muscular fitness was positively associated with cognitive flexibility (Cohen's $d = 0.18$) and working memory (Cohen's $d = 0.14$) in children and adolescents (Robinson et al., 2023). Similar to cardiorespiratory fitness, the association between muscular fitness and executive functions may be explained by changes in brain structure and function (e.g., white matter volume, brain-derived neurotrophic factor) (Esteban-Cornejo et al., 2019; Isaac et al., 2021). Muscular fitness is associated with notable health improvements in children and adolescents, including reductions in metabolic risk factors and improvements in psychological outcomes (J. Smith et al., 2014), each of which may improve executive functions (Kamijo et al., 2012; D. Lubans et al., 2016). While promising, limited studies have examined the mediating effects of fitness (particularly muscular fitness) in the relationship with executive functions in children.

The "skill acquisition" hypothesis suggests that the process of learning new skills might explain the benefits of physical activity for cognition. In support of this idea, reviews from the past few years note a positive association between motor skill competency and executive functions in children and adolescents (Gandotra et al., 2022; Hill et al., 2023; Willoughby & Hudson, 2023), with a recent meta-analysis indicating a small consistent association ($r = 0.18$) (Bao et al., 2024). The theory is that cognitively complex activity (including the acquisition of new skills) relies on shared functional regions within the brain, notably the prefrontal cortex, the cerebellum, and the basal ganglia, which are believed to underpin the association between physical activity and executive functions (Diamond, 2000; Leisman et al., 2016; Pangelinan et al., 2011). Despite few experimental studies, the existing evidence suggests that physical activity programmes may benefit the development of executive functions in children by improving their motor competence (MC) (Mulvey et al., 2018; Vazou et al., 2020).

As outlined, emerging evidence suggests cardiorespiratory fitness, muscular fitness and motor competence may mediate the relationship between physical activity and executive functions in children. However, only a few studies have formally tested the fitness and skill acquisition hypotheses via mediation analyses (Muntaner-Mas et al., 2022; Spanou et al., 2022). While these studies have provided valuable findings, they did not test the relative contributions of cardiorespiratory fitness, muscular fitness, and motor competence to executive functions. To

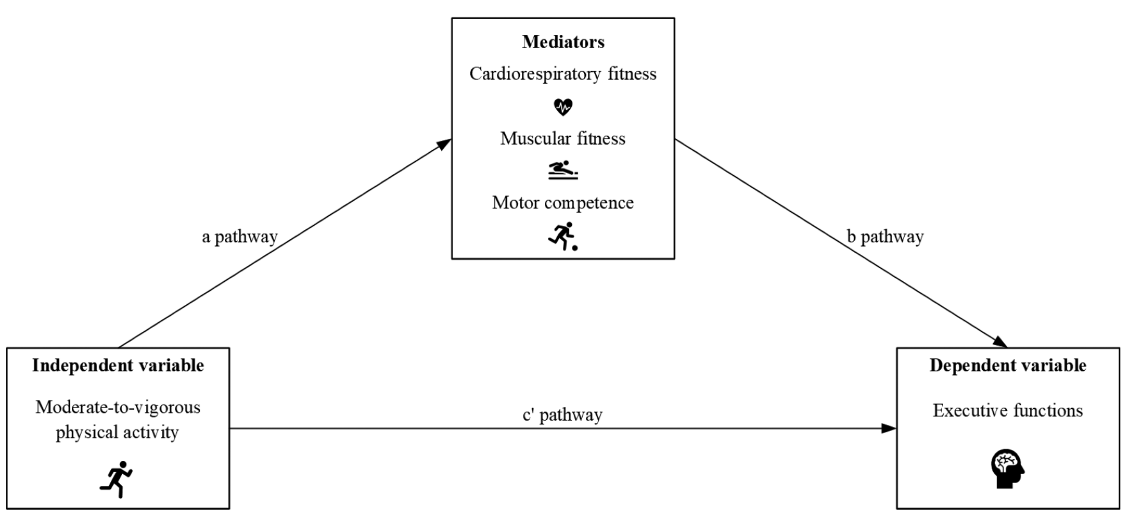

Figure 1. Hypothesized associations between moderate-to-vigorous physical activity, cardiorespiratory fitness, muscular fitness, motor competence and executive functions.

address these research gaps, our study aimed to explore the mediating roles of these three components in the association between school-hour moderate-to-vigorous physical activity (MVPA) and executive functions in children (Figure 1). Our research questions were as follows:

(1) Is physical activity positively associated with cardiorespiratory fitness, muscular fitness, and motor competence (a pathway)?
(2) Is cardiorespiratory fitness, muscular fitness, and motor competence positively associated with executive functions (b pathway)?
(3) Is physical activity positively associated with executive functions (c`pathway)?
(4) Will cardiorespiratory fitness, muscular fitness, and motor competence mediate the cross-sectional associations between physical activity and executive functions?

We hypothesized that cardiorespiratory fitness, muscular fitness, and motor competence would be positively associated with physical activity and mediate the cross-sectional relationship with executive functions.

Methods

Study design and participants

We used baseline data from the Learning to Lead (L2L) cluster randomised controlled trial. Detailed information about this programme is available in our published protocol paper (Wade et al., 2023). Data were collected by trained researchers between 2022 (cohort 1) and 2023 (cohort 2) across 20 primary schools in the state of New South Wales (NSW), Australia. In total, 675 children (7–11 years, 49.5% girls) who were in Grades 3 and 4 were eligible and included in the current cross-sectional study. We obtained written informed assent from students and written consent from their parents or legal guardians. The study was approved by the human research ethics committee of the University of Newcastle (approval number: H-2020–0109) and the NSW Department of Education (reference number: 2020143). The L2L trial was prospectively registered with the Australian New Zealand Clinical Trials Registry (reference number: ACTRN12621000376842).

Measurement

Baseline data regarding participants' demographic information (e.g., age, socioeconomic status) were collected via an online survey using electronic tablets.

Physical activity

Children's physical activity levels were assessed by wrist-worn accelerometers (ActiGraph GT9X). Participants wore the device on their non-dominant wrist and were asked to wear them during the school day for five school days (approximately between the hours of 9:00 am and 3:00 pm). Physical activity intensity was categorised as light, moderate, and vigorous using validated cut points (Chandler et al., 2016).

Physical fitness

Cardiorespiratory fitness was evaluated using the 20 m Multistage Fitness Test. This test has shown moderate-to-high validity to estimate maximum oxygen uptake in children (Mayorga-Vega et al., 2015). The children were required to run between two lines set up 20 m apart. The total score was the number of completed laps.

Muscular fitness was assessed by the standing long jump, which has shown good validity and reliability to assess muscular fitness in children and adolescents (Castro-Piñero et al., 2010; Ruiz et al., 2011). Participants performed two jumps, with the furthest jump recorded in centimetres as their final score.

Motor competence

Motor competence was assessed using a subset of object control skills (throwing, catching, and kicking) from the Test of Gross Motor Development 3 (TGMD-3) (Webster & Ulrich, 2017). Children were filmed performing three trials of each of the three skills (including an initial practice trial that was not assessed). These skills were selected based on their transferability into a variety of different sports that are popular among Australian children. Each skill in the recording was assessed according to skill-specific performance criteria by trained research assistants. Each skill component was scored a "1" if performed correctly, or "0" if performed incorrectly. This procedure was completed for each of the two primary trials, and trial scores were summed to calculate a total score for each skill. An overall object control movement skills score was calculated by summing the scores from all three skills.

Executive functions

Inhibitory control and cognitive flexibility were measured using two assessments from the National Institute of Health Toolbox for the Assessment of Neurological and Behavioural Function. Participants completed both tests on an iPad app in a quiet room alongside a maximum of 20 other students completing the tests at the same time. Instructions for both tests were explained by a member of the research team and were also shown on the screen. All participants wore headphones for the duration of the test battery, which took approximately 10 min to complete. Inhibitory control was assessed using the "Flanker Inhibitory Control and Attention Test" (version for children between 8 and 11 years). In this population, scores derived from this test have shown convergent validity and good test–retest reliability (ICC = 0.95, 95% CI = 0.92–0.97) (Weintraub et al., 2013). Inhibition performance was calculated as a combination of speed and accuracy and produced a score between 0 and 10, with a higher score indicating greater performance. Cognitive flexibility was assessed by the Dimensional Change Card Sort Test (version for children between 8 and 11 years). Scores derived from this test have also shown good test–retest reliability (ICC = 0.94, 95% CI = 0.92–0.96), and validity when used with children and adolescents (Weintraub et al., 2013). Based on a combination of test accuracy and speed,

Table 1. Characteristics of the study sample.

	Overall ($n = 675^a$)		Boys ($n = 336$, 50.5%)		Girls ($n = 329$, 49.5%)			
	n (%)	Mean (SD)	n (%)	Mean (SD)	n (%)	Mean (SD)	Statistic (χ^2/t)	*P* value
Cultural background, n (%)								
Australian	606 (90.2%)		300 (89.3%)		302 (91.8%)		1.22	0.270
Other	66 (9.8%)		36 (10.7%)		27 (8.2%)			
Socioeconomic status, n (%)								
Low	66 (9.9%)		32 (9.6%)		33 (10.1%)		0.83	0.659
Medium	512 (76.4%)		253 (75.5%)		254 (77.4%)			
High	92 (13.7%)		50 (14.9%)		41 (12.5%)			
Age	672	8.7 (0.7)	336	8.7 (0.7)	329	8.6 (0.7)	1.87	0.062
MVPA (minutes)	675	34.3 (14.1)	336	39.6 (14.8)	329	29.0 (10.8)	10.52	<0.001
MC (scores)	643	14.4 (3.5)	316	15.9 (3.2)	320	12.9 (3.2)	11.74	<0.001
Cardiorespiratory fitness (laps)	653	26.2 (15.4)	327	29.6 (17.6)	318	22.7 (12.0)	5.80	<0.001
Muscular fitness (cm)	662	119.7 (22. 6)	329	125.6 (23.5)	325	114.0 (19.9)	6.78	<0.001
Inhibitory control (scores)	666	7.4 (1.1)	331	7.5 (1.1)	327	7.4 (1.0)	1.28	0.202
Cognitive flexibility (scores)	666	6.9 (1.1)	331	6.9 (1.1)	327	6.8 (1.1)	0.63	0.532

[a] = there was missing data for the sex of 10 participants.

the test provides a score between 0 and 10, with higher scores indicating superior performance.

Statistical analysis

To maximise the number of students in the current study whilst preserving the validity of the measurement, we conducted ICC analyses comparing two or more and three or more days of valid accelerometry. The values were as follows: two or more, ICC = 0.75, and three or more, ICC = 0.83. According to previous studies, an ICC of 0.75, calculated from two or more days, is considered acceptable for accelerometry (Antczak et al., 2021; Barboza et al., 2021; Ridley et al., 2009), accordingly, we used data with two or more days of valid wear time. Descriptive analyses (the Chi-square and independent t-test) and bivariate correlations between physical activity, motor competence, cardiorespiratory fitness, muscular fitness, and executive functions (alpha levels set at $p < 0.05$) were conducted in IBM SPSS Statistics for Windows, V.28.0 (IBM, Armonk, New York, USA) and are presented in Table 1.

We used multi-level structural equation modelling in Mplus version 8.10 to investigate whether cardiorespiratory fitness, muscular fitness, or motor competence mediate the cross-sectional associations between MVPA and executive functions (indirect effect). These questions were investigated using the models shown in Figures 2 and 3. To address missing data and

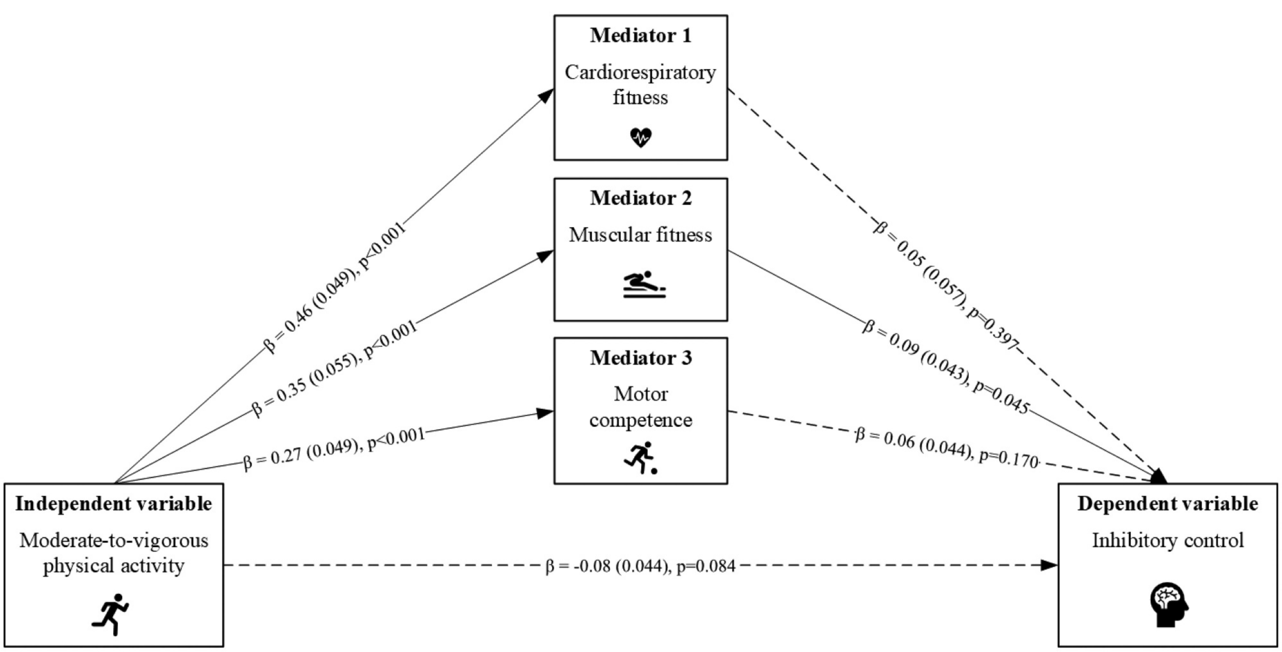

Figure 2. The mediating association between MVPA and inhibitory control in overall sample ($n = 664$). (Note: adjusted for socioeconomic status and sex, the numbers in the brackets refer to SE, solid lines represent significant β coefficients and dashed lines indicate non-significant β coefficients)

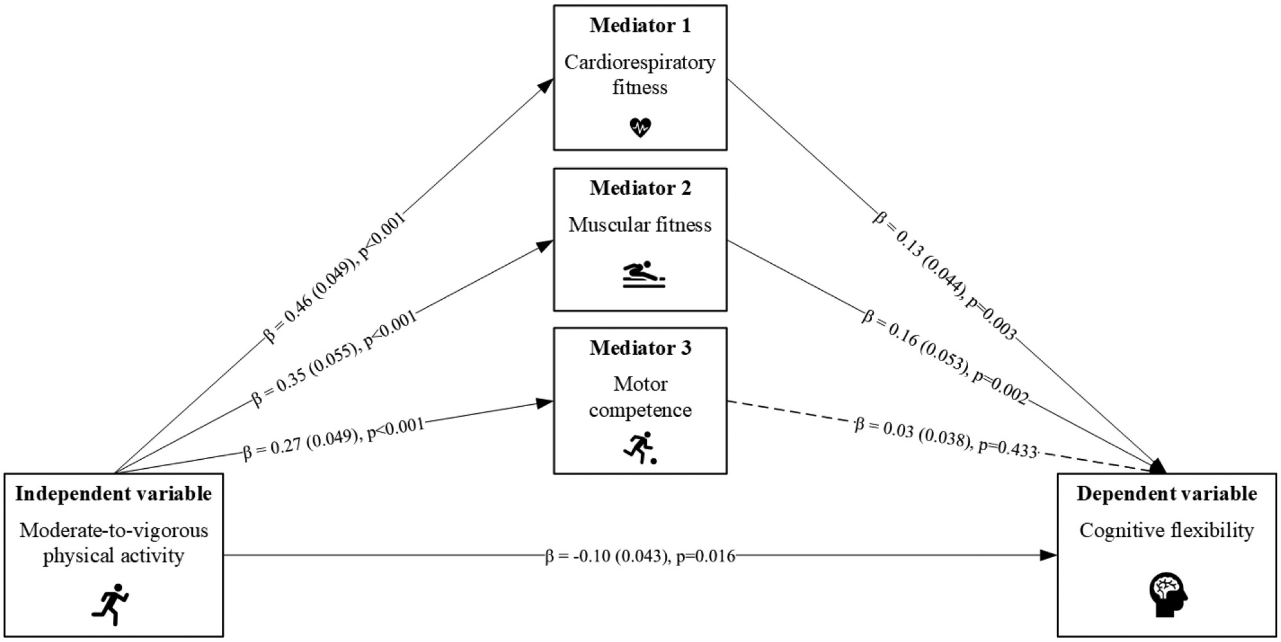

Figure 3. The mediating association between MVPA and cognitive flexibility in overall sample ($n = 664$). (Note: adjusted for socioeconomic status and sex, the numbers in the brackets refer to SE, solid lines represent significant β coefficients and dashed lines indicate non-significant β coefficients)

Table 2. Pearson's bivariate correlations among variables in children.

Coefficients (sample size)	1	2	3	4	5	6
1. MVPA	1					
2. CRF	0.462** (653)	1				
3. MF	0.387** (662)	0.590** (649)	1			
4. MC	0.389** (643)	0.363** (627)	0.413** (636)	1		
5. Inhibitory control	0.012 (666)	0.093* (647)	0.122** (656)	0.084* (637)	1	
6. Cognitive flexibility	0.039 (666)	0.197** (647)	0.218** (656)	0.109** (637)	0.332** (666)	1

MVPA = moderate-to-vigorous physical activity; CRF = cardiorespiratory fitness; MF = muscular fitness; MC = motor competence. *. Correlation is significant at the 0.05 level (2-tailed); **. Correlation is significant at the 0.01 level (2-tailed).

the non-independence of students clustering within schools, we applied robust maximum likelihood estimation by adjusting standard errors using a sandwich estimator. Each outcome was standardised by converting them into z-scores before analysis. Two multiple mediator models were used to estimate the indirect effects of physical activity on inhibitory control and cognitive flexibility. The goodness of model fits were evaluated using χ^2 (Chi-square statistics), the Comparative Fit Index (CFI) (Bentler, 1990), the Tucker-Lewis Index (TLI) (Tucker & Lewis, 1973), the Root Mean Square Error of Approximation (RMSEA) (Browne & Cudeck, 1992) and their 90% confidence interval (90% CI). A value of TLI and CFI greater than 0.95 and an RMSEA less than 0.05 indicate an adequate model fit to the observed data (Hu & Bentler, 1999). Each model adjusted for socioeconomic status and sex. Each model tested the relationship between the independent variable and the hypothesised mediators (a path); the mediators and the dependent variables (b path). Then, a series of product of coefficients (a path × b path) were tested to calculate the mediated estimates for each hypothesised mediator (cardiorespiratory fitness, muscular fitness, and motor competence). The indirect estimates were considered significant where $p < 0.05$. The magnitude of the associations can be described as small (0.10–0.29), moderate (0.30–0.49), and strong (≥0.50) (Cohen, 2013).

Results

The sample characteristics are displayed in Table 1. Among 675 children (with a mean of 8.67 ± 0.67 years), 49.5% were female, and 90.2% of them were born in Australia. Table 2 outlines the bivariate correlations among all measures. Figure 2 presents the results of direct estimates of MVPA and mediators on inhibitory control in children. The mediation model for inhibitory control provided an adequate fit to the data with χ^2 (18) = 8.126, CFI = 0.994, TLI = 0.979, RMSEA = 0.031 and 90% CI = 0.000–-0.067. Figure 3 shows the results of direct estimates of MVPA and mediators on cognitive flexibility in children. The mediation

Table 3. The indirect estimates of MVPA on executive functions through mediators.

	Overall ($n = 675$)		
Pathways	β	SE	p
MVPA to inhibitory control via CRF	0.02	0.027	0.404
MVPA to inhibitory control via MF	0.03	0.014	0.027
MVPA to inhibitory control via MC	0.02	0.012	0.185
MVPA to cognitive flexibility via CRF	0.06	0.021	0.004
MVPA to cognitive flexibility via MF	0.06	0.021	0.005
MVPA to cognitive flexibility via MC	0.01	0.010	0.435

MVPA, moderate-to-vigorous physical activity; CRF, cardiorespiratory fitness; MF, muscular fitness; MC, motor competence; β, standardised coefficients; SE, standard error.

model for cognitive flexibility also provided an adequate fit to the data, χ^2 (18) = 605.754, CFI = 0.994, TLI = 0.979, RMSEA = 0.032 and 90% CI = 0.000–0.069.

MVPA on hypothesised mediators (a pathway – action theory tests)

MVPA was associated with cardiorespiratory fitness ($\beta = 0.46$, SE = 0.049, $p < 0.001$), muscular fitness ($\beta = 0.35$, SE = 0.055, $p < 0.001$) and motor competence ($\beta = 0.27$, SE = 0.049, $p < 0.001$).

Hypothesised mediators on executive functions (b pathway – conceptual theory tests)

Muscular fitness was associated with inhibitory control ($\beta = 0.09$, SE = 0.043, $p = 0.045$) and cognitive flexibility ($\beta = 0.16$, SE = 0.053, $p = 0.002$), while cardiorespiratory fitness was only associated with cognitive flexibility ($\beta = 0.13$, SE = 0.044, $p = 0.003$). No significant associations were observed between motor competence and measures of executive function.

MVPA on executive functions (c` pathway – including mediators)

MVPA was negatively associated with cognitive flexibility ($\beta = -0.10$, SE = 0.043, $p = 0.016$), while no association was observed between MVPA and inhibitory control.

Significance of the indirect effects (ab pathway – mediation tests)

Table 3 displays the indirect estimates of MVPA on inhibitory control and cognitive flexibility. Cardiorespiratory fitness mediated the association between MVPA and cognitive flexibility in the overall sample ($\beta = 0.06$, SE = 0.021, $p = 0.004$). Muscular fitness mediated the relationship between MVPA and inhibitory control in the overall sample ($\beta = 0.03$, SE = 0.014, $p = 0.027$). Muscular fitness was also a significant mediator of the effect of MVPA on cognitive flexibility ($\beta = 0.06$, SE = 0.021, $p = 0.005$) in the overall sample. We did not observe indirect effects of motor competence in the relationship between MVPA and executive functions in children.

Discussion

The aim of our study was to examine whether cardiorespiratory fitness, muscular fitness, or motor competence mediated the cross-sectional association between MVPA and executive functions in children. The findings indicated that cardiorespiratory fitness mediated the association between MVPA and cognitive flexibility, while muscular fitness mediated the relationship between MVPA and both inhibitory control and cognitive flexibility. Conversely, we did not find a mediating role of motor competence on either outcome.

The "fitness" hypothesis postulates that participation in physical activity of sufficient duration and intensity can produce cardiorespiratory fitness gains, which may subsequently enhance cognition (Petruzzello et al., 1997; Tomporowski & Pesce, 2019). In line with this hypothesis, our findings suggested that cardiorespiratory fitness was positively associated with executive functions in children, which is consistent with reviews on the topic (De Greeff et al., 2018; Hillman et al., 2008; Van Waelvelde et al., 2020). Notably, few studies have formally examined the mediation of cardiorespiratory fitness in children (Visier-Alfonso et al., 2021; Yangüez et al., 2021). Specifically, we found that cardiorespiratory fitness mediated the relationship between MVPA and cognitive flexibility but not for inhibitory control. Research on the mediating effects of cardiorespiratory fitness, as assessed by the 20-m shuttle run test, has yielded mixed results. Some studies have reported similar findings to the current study (Yangüez et al., 2021), while others have found that cardiorespiratory fitness mediates inhibitory control but not cognitive flexibility (Visier-Alfonso et al., 2021). These discrepancies may be partly due to methodological differences in how cardiorespiratory fitness is measured. For instance, while some studies have used direct measures of maximal oxygen consumption, in the current study, cardiorespiratory fitness was assessed based on the number of completed laps in the shuttle run. The finding that cardiorespiratory fitness mediated the relationship between MVPA and cognitive flexibility may be explained by several hypotheses.

Cardiorespiratory fitness can contribute to greater cerebral circulation, and an upregulation of neurotrophins (e.g., brain-derived neurotrophic factor) that contribute to executive function performance (Stimpson et al., 2018). Alternatively, there is a behavioural explanation for cardiorespiratory fitness as a mediator of executive functions. Aerobic exercises demand varying levels of cognitive engagement, which may pose challenges to children's executive functions (Best, 2010; Tomporowski & Pesce, 2019). In particular, contextual interference arises during participation in aerobic exercises, compelling children's need to create, monitor and modify their actions to accomplish diverse and complex exercise tasks (Best, 2010; Tomporowski & Pesce, 2019). This process necessitates the involvement of executive processes, and the cognitive skills essential for engaging in aerobic exercises may transfer to performance on executive function tasks (Best, 2010).

We found that muscular fitness was a mediator between MVPA and both of our executive functioning outcomes. The relationship between muscular fitness and executive functions in children is still an emerging field of research, but our findings are consistent with the existing literature (Robinson et al., 2023; J. J. Smith et al., 2014). A recent review found that muscular fitness is positively associated with cognitive flexibility (Cohen's $d = 0.18$) and working memory (Cohen's $d = 0.14$) in children and adolescents (Robinson et al., 2023). Further, there is evidence that higher levels of muscular fitness are associated with greater inhibitory control and cognitive flexibility (Solis-Urra et al., 2021; Zeng et al., 2023). There is also evidence of a positive association between muscular fitness and white matter volume in children (Esteban-Cornejo et al., 2019). However, it is important to acknowledge the differences in how muscular fitness was assessed across studies. For example, several studies have used composite measures, such as the combination of handgrip strength and the standing long jump (Esteban-Cornejo et al., 2019; Solis-Urra et al., 2021), or a broader battery of tests, including the assessment of grip strength, pull ups (boys), sit-ups (girls) and standing long jump (Zeng et al., 2023). In contrast, our study assessed muscular fitness solely using the standing long jump test. These methodological differences in how muscular fitness is assessed must be considered when comparing our results with those of other studies.

Interestingly, our study has shown that muscular fitness was a predictor of executive functioning, independently of cardiorespiratory fitness. This relationship may be explained, at least in part, by the relationship of muscular fitness to brain structure and functions. The activation of skeletal muscle may stimulate the release of neurotrophins (such as irisin and brain-derived neurotrophic factor), which may facilitate executive functions (Isaac et al., 2021). Therefore, it may be the case that activities that are particularly taxing on skeletal muscle (e.g., resistance exercise), and thus contribute to muscular fitness, may be especially effective on executive functions. Clearly, there is a need for further research on the relationship between muscular fitness and executive functions.

The "skill" hypothesis proposed that physical activity participation can facilitate the acquisition of motor skill competency, which subsequently improves cognitive function. Engagement in cognitively complex and/or novel motor skill tasks may lead to improvements in executive functions. There is evidence that motor competence is positively associated with executive functions in children and adolescents (Gandotra et al., 2022; Hill et al., 2023; Willoughby & Hudson, 2023). Recently, findings from a meta-analysis suggest that motor competence ($r = 0.18$) is associated with executive functions in children and adolescents (Bao et al., 2024). Further, emerging evidence suggests that motor competence may influence the relationship between physical activity and executive functions (Hill et al., 2023; Willoughby & Hudson, 2023). The underlying mechanisms may be related to the use of functional regions within the brain, such as prefrontal cortex, the cerebellum, and the basal ganglia that are common to both motor and cognitive activities (Diamond, 2000; Leisman et al., 2016). Contrary to our hypothesis, we did not find that motor competence mediated the association between MVPA and executive functions. Notably, few studies have formally investigated the potential mediating role of motor competence in this relationship. Among them, Spanou et al. (2022), found that motor competence, assessed using the Bruininks – Oseretsky Test of Motor Proficiency-Second Edition (BOT-2), mediated the association between physical activity and executive functions in children. Given the limited research on the potentially mediating role of motor competence, future longitudinal and experimental research is needed to better understand the temporality of this relationship and the causal pathways linking motor competence, physical activity, and executive functions.

To date, much of the existing research has focused on the relationship between cardiorespiratory fitness and executive functioning, with substantially less attention given to the potential contributions of muscular fitness and motor competence (De Greeff et al., 2018; Xue et al., 2019). This imbalance leaves a gap in our understanding of the specific aspects of physical activity that may influence cognitive development in children. The current study addresses this gap by testing the relative contributions of cardiorespiratory fitness, muscular fitness, and motor competence to children's executive functions. Our findings lend support to the "fitness hypothesis", suggesting that physical activity-induced improvements in both cardiorespiratory and muscular fitness are significantly associated with enhanced executive functioning performance. Importantly, this is one of the few studies to formally test and compare the relative impact of these distinct aspects of physical fitness and competence on executive functions, thereby providing a more comprehensive understanding of the intricate relationships between physical activity and cognitive development.

Strengths and limitations

To our knowledge, this is the first study to formally test cardiorespiratory fitness, motor competence, and muscular fitness as mediators in the relationship between device-assessed physical activity and executive functions in children. We used a multilevel modelling approach, which is considered best practice for analysing clustered data. However, several limitations should be considered. First, our findings are based on a cross-sectional study design, preventing the analysis of a causal relationship between MVPA and executive functions in children. There are potential bi-directional associations between physical activity and motor competence, as well as cardiorespiratory and muscular fitness in children and adolescents (Barnett et al., 2022). For example, improvements in motor competence may lead to increased physical activity among youth. Conversely, increasing physical activity could also enhance motor competence. Future experimental research is needed to establish the temporal order of these relationships. Second, although inhibition, cognitive flexibility, and working memory are considered the three core executive functions (Zelazo, 2020), we did not measure working memory due to logistical constraints. We used the NIH toolbox that includes a measure of working memory that requires one-on-one administration. This was not feasible, as we needed to test several students simultaneously. Future research should include working memory to provide a more comprehensive account of the relationship between physical activity and executive functions. Third, our assessment of motor competence was limited to three object control skills. It is possible that our findings may have differed if we used a more comprehensive battery that also included locomotor and stability skills.

Conclusion

Our study examined cardiorespiratory fitness, muscular fitness, and motor competence as mediators of the association between MVPA and executive functions in children. We found that both cardiorespiratory fitness and muscular fitness mediated the association between MVPA and executive functions. These findings indicate that physical activity participation may contribute to enhanced cardiorespiratory fitness and muscular fitness, and changes in these skills are associated with better executive functions in children. However, further experimental studies are encouraged to explore the causal mechanisms underlying this relationship. Data from the L2L trial will be instrumental in determining the efficacy of physical activity interventions on executive functions, and in testing the fitness and skill hypotheses explored in the current study. Future research should continue to investigate these pathways to develop targeted strategies that optimize both physical and cognitive development in young populations. Overall, our findings suggest that physical activity has benefits for both physical fitness and the development of executive functions of children.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

Data are available upon reasonable request.

References

Antczak, D., Lonsdale, C., Del Pozo Cruz, B., Parker, P., & Sanders, T. (2021). Reliability of GENEActiv accelerometers to estimate sleep, physical activity, and sedentary time in children. *The International Journal of Behavioral Nutrition and Physical Activity*, *18*(1), 1–11. https://doi.org/10.1186/s12966-021-01143-6

Bao, R., Wade, L., Leahy, A. A., Owen, K. B., Hillman, C. H., Jaakkola, T., & Lubans, D. R. (2024). Associations between motor competence and executive functions in children and adolescents: A systematic review and meta-analysis. *Sports Medicine*, *54*(8), 2141–2156. https://doi.org/10.1007/s40279-024-02040-1

Barboza, L. L., Gandarela, L., Santana, J. G. S., Silva, E. C. M., Machado, E. S., Silva, R. J. S., Gomes, T. N., & Silva, D. R. (2021). Agreement between different days of activpal and actigraph GT3X measurement of sedentary behavior and physical activity during the school hours in elementary children. *Journal for the Measurement of Physical Behaviour*, *4*(2), 111–117. https://doi.org/10.1123/jmpb.2020-0025

Barnett, L. M., Webster, E. K., Hulteen, R. M., De Meester, A., Valentini, N. C., Lenoir, M., Pesce, C., Getchell, N., Lopes, V. P., Robinson, L. E., Brian, A., & Rodrigues, L. P. (2022). Through the looking glass: A systematic review of longitudinal evidence, providing new insight for motor competence and health. *Sports Medicine*, *52*(4), 875–920. https://doi.org/10.1007/s40279-021-01516-8

Bentler, P. M. (1990). Comparative fit indexes in structural models. *Psychological Bulletin*, *107*(2), 238. https://doi.org/10.1037/0033-2909.107.2.238

Best, J. R. (2010). Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Developmental Review*, *30*(4), 331–351. https://doi.org/10.1016/j.dr.2010.08.001

Biddle, S. J., Ciaccioni, S., Thomas, G., & Vergeer, I. (2019). Physical activity and mental health in children and adolescents: An updated review of reviews and an analysis of causality. *Psychology of Sport & Exercise*, *42*, 146–155. https://doi.org/10.1016/j.psychsport.2018.08.011

Browne, M. W., & Cudeck, R. (1992). Alternative ways of assessing model fit. *Sociological Methods & Research*, *21*(2), 230–258. https://doi.org/10.1177/0049124192021002005

Castro-Piñero, J., Ortega, F. B., Artero, E. G., Girela-Rejón, M. J., Mora, J., Sjöström, M., & Ruiz, J. R. (2010). Assessing muscular strength in youth: Usefulness of standing long jump as a general index of muscular fitness. *The Journal of Strength & Conditioning Research*, *24*(7), 1810–1817. https://doi.org/10.1519/JSC.0b013e3181ddb03d

Chandler, J., Brazendale, K., Beets, M., & Mealing, B. (2016). Classification of physical activity intensities using a wrist-worn accelerometer in 8–12-year-old children. *Pediatric Obesity*, *11*(2), 120–127. https://doi.org/10.1111/ijpo.12033

Chaput, J.-P., Willumsen, J., Bull, F., Chou, R., Ekelund, U., Firth, J., Jago, R., Ortega, F. B., & Katzmarzyk, P. T. (2020). 2020 WHO guidelines on physical activity and sedentary behaviour for children and adolescents aged 5–17 years: Summary of the evidence. *The International Journal of Behavioral Nutrition and Physical Activity*, *17*(1). https://doi.org/10.1186/s12966-020-01037-z

Ciria, L. F., Román-Caballero, R., Vadillo, M. A., Holgado, D., Luque-Casado, A., Perakakis, P., & Sanabria, D. (2023). An umbrella review of randomized control trials on the effects of physical exercise on cognition. *Nature Human Behaviour*, *7*(6), 928–941. https://doi.org/10.1038/s41562-023-01554-4

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Academic press.

Cortés Pascual, A., Moyano Muñoz, N., & Quilez Robres, A. (2019). The relationship between executive functions and academic performance in primary education: Review and meta-analysis. *Frontiers in Psychology*, *10*, 1582. https://doi.org/10.3389/fpsyg.2019.01582

De Greeff, J. W., Bosker, R. J., Oosterlaan, J., Visscher, C., & Hartman, E. (2018). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: A meta-analysis. *Journal of Science & Medicine in Sport*, *21*(5), 501–507. https://doi.org/10.1016/j.jsams.2017.09.595

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development*, *71*(1), 44–56. https://doi.org/10.1111/1467-8624.00117

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*(1), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Diamond, A., & Ling, D. S. (2019). Aerobic-exercise and resistance-training interventions have been among the least effective ways to improve executive functions of any method tried thus far. *Developmental Cognitive Neuroscience*, *37*, 100572. https://doi.org/10.1016/j.dcn.2018.05.001

Esteban-Cornejo, I., Rodriguez-Ayllon, M., Verdejo-Roman, J., Cadenas-Sanchez, C., Mora-Gonzalez, J., Chaddock-Heyman, L., Raine, L. B., Stillman, C. M., Kramer, A. F., Erickson, K. I., Catena, A., Ortega, F. B., & Hillman, C. H. (2019). Physical fitness, white matter volume and academic performance in children: Findings from the ActiveBrains and FITKids2 projects. *Frontiers in Psychology*, *10*, 208. https://doi.org/10.3389/fpsyg.2019.00208

Gandotra, A., Csaba, S., Sattar, Y., Cserényi, V., Bizonics, R., Cserjesi, R., & Kotyuk, E. (2022). A meta-analysis of the relationship between motor skills and executive functions in typically-developing children. *Journal of Cognition and Development*, *23*(1), 83–110. https://doi.org/10.1080/15248372.2021.1979554

García-Hermoso, A., Ramírez-Vélez, R., Lubans, D. R., & Izquierdo, M. (2021). Effects of physical education interventions on cognition and academic performance outcomes in children and adolescents: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *55*(21), 1224–1232. https://doi.org/10.1136/bjsports-2021-104112

Gardiner, E., & Iarocci, G. (2018). Everyday executive function predicts adaptive and internalizing behavior among children with and without autism spectrum disorder. *Autism Research*, *11*(2), 284–295. https://doi.org/10.1002/aur.1877

Hill, P. J., McNarry, M. A., Mackintosh, K. A., Murray, M. A., Pesce, C., Valentini, N. C., Getchell, N., Tomporowski, P. D., Robinson, L. E., & Barnett, L. M. (2023). The influence of motor competence on broader aspects of health: A systematic review of the longitudinal associations between motor competence and cognitive and social-emotional outcomes. *Sports Medicine*, *54*(2), 375–427. https://doi.org/10.1007/s40279-023-01939-5

Hillman, C. H., Erickson, K. I., & Kramer, A. F. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. *Nature Reviews Neuroscience*, *9*(1), 58–65. https://doi.org/10.1038/nrn2298

Hillman, C. H., McAuley, E., Erickson, K. I., Liu-Ambrose, T., & Kramer, A. F. (2019). On mindful and mindless physical activity and executive function: A response to diamond and Ling. *Developmental Cognitive Neuroscience*, *37*(2016), 100529. https://doi.org/10.1016/j.dcn.2018.01.006

Hollocks, M. J., Jones, C. R., Pickles, A., Baird, G., Happé, F., Charman, T., & Simonoff, E. (2014). The association between social cognition and executive functioning and symptoms of anxiety and depression in adolescents with autism spectrum disorders. *Autism Research*, *7*(2), 216–228. https://doi.org/10.1002/aur.1361

Hu, L. T., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal*, *6*(1), 1–55. https://doi.org/10.1080/10705519909540118

Isaac, A. R., Lima-Filho, R. A., & Lourenco, M. V. (2021). How does the skeletal muscle communicate with the brain in health and disease? *Neuropharmacology, the Neuropharmacology of Social Behavior: From Bench to Bedside*, *197*, 108744. https://doi.org/10.1016/j.neuropharm.2021.108744

Jacob, R., & Parkinson, J. (2015). The potential for school-based interventions that target executive function to improve academic achievement: A review. *Review of Educational Research*, *85*(4), 512–552. https://doi.org/10.3102/0034654314561338

Kamijo, K., Khan, N. A., Pontifex, M. B., Scudder, M. R., Drollette, E. S., Raine, L. B., Evans, E. M., Castelli, D. M., & Hillman, C. H. (2012). The relation of adiposity to cognitive control and scholastic achievement in preadolescent children. *Obesity (Silver Spring)*, *20*(12), 2406–2411. https://doi.org/10.1038/oby.2012.112

Khan, N. A., & Hillman, C. H. (2014). The relation of childhood physical activity and aerobic fitness to brain function and cognition: A review. *Pediatric Exercise Science*, *26*(2), 138–146. https://doi.org/10.1123/pes.2013-0125

Leisman, G., Moustafa, A., & Shafir, T. (2016). Thinking, walking, talking: Integratory motor and cognitive brain function. *Frontiers in Public Health*, *4*, 4. https://doi.org/10.3389/fpubh.2016.00094

Lubans, D., Richards, J., Hillman, C., Faulkner, G., Beauchamp, M., Nilsson, M., Kelly, P., Smith, J., Raine, L., & Biddle, S. (2016). Physical activity for cognitive and mental health in youth: A systematic review of mechanisms. *Pediatrics*, *138*(3), e20161642. https://doi.org/10.1542/peds.2016-1642

Lubans, D. R., Leahy, A. A., Mavilidi, M. F., & Valkenborghs, S. R. (2021). *Physical activity, fitness, and Executive functions in youth: Effects, moderators, and mechanisms*. Springer International Publishing. https://doi.org/10.1007/7854_2021_271

Mamrot, P., & Hanć, T. (2019). The association of the executive functions with overweight and obesity indicators in children and adolescents: A literature review. *Neuroscience & Biobehavioral Reviews*, *107*, 59–68. https://doi.org/10.1016/j.neubiorev.2019.08.021

Mayorga-Vega, D., Aguilar-Soto, P., & Viciana, J. (2015). Criterion-related validity of the 20-m shuttle run test for estimating cardiorespiratory fitness: A meta-analysis. *Journal of Sports Science & Medicine*, *14*(3), 536.

Mulvey, K. L., Taunton, S., Pennell, A., & Brian, A. (2018). Head, toes, knees, SKIP! Improving Preschool Children's executive function through a motor competence intervention. *Journal of Sport & Exercise Psychology*, *40*(5), 233–239. https://doi.org/10.1123/jsep.2018-0007

Muntaner-Mas, A., Mazzoli, E., Abbott, G., Mavilidi, M. F., & Galmes-Panades, A. M. (2022). Do physical fitness and executive function mediate the relationship between physical activity and academic achievement? An examination using structural equation modelling. *Children*, *9*(6), 823. https://doi.org/10.3390/children9060823

Pangelinan, M. M., Zhang, G., Vanmeter, J. W., Clark, J. E., Hatfield, B. D., & Haufler, A. J. (2011). Beyond age and gender: Relationships between cortical and subcortical brain volume and cognitive-motor abilities in school-age children. *Neuroimage*, *54*(4), 3093–3100. https://doi.org/10.1016/j.neuroimage.2010.11.021

Petruzzello, S. J., Han, M., & Nowell, P. (1997). The influence of physical fitness and exercise upon cognitive functioning: A meta-analysis. *Journal of Sport & Exercise Psychology*, *19*(3), 249–277. https://doi.org/10.1123/jsep.19.3.249

Ridley, K., Olds, T., Hands, B., Larkin, D., & Parker, H. (2009). Intra-individual variation in children's physical activity patterns: Implications for measurement. *Journal of Science & Medicine in Sport*, *12*(5), 568–572. https://doi.org/10.1016/j.jsams.2008.09.009

Riggs, N. R., Jahromi, L. B., Razza, R. P., Dillworth-Bart, J. E., & Mueller, U. (2006). Executive function and the promotion of social–emotional competence. *Journal of Applied Developmental Psychology*, *27*(4), 300–309. https://doi.org/10.1016/j.appdev.2006.04.002

Robinson, K., Riley, N., Owen, K., Drew, R., Mavilidi, M. F., Hillman, C. H., Faigenbaum, A. D., Garcia-Hermoso, A., & Lubans, D. R. (2023). Effects of resistance training on academic outcomes in school-aged youth: A systematic review and meta-analysis. *Sports Medicine*, *53*(11), 2095–2109. https://doi.org/10.1007/s40279-023-01881-6

Ruiz, J. R., Castro-Piñero, J., España-Romero, V., Artero, E. G., Ortega, F. B., Cuenca, M. M., Jimenez-Pavón, D., Chillón, P., Girela-Rejón, M. J., Mora, J., Gutiérrez, Á., Suni, J., Sjöström, M., & Castillo, M. J. (2011). Field-based fitness assessment in young people: The ALPHA health-related fitness test battery for children and adolescents. *British Journal of Sports Medicine*, *45*(6), 518–524. https://doi.org/10.1136/bjsm.2010.075341

Singh, A. S., Saliasi, E., Van Den Berg, V., Uijtdewilligen, L., De Groot, R. H., Jolles, J., Andersen, L. B., Bailey, R., Chang, Y.-K., Diamond, A., Ericsson, I., Etnier, J. L., Fedewa, A. L., Hillman, C. H., McMorris, T., Pesce, C., Pühse, U., Tomporowski, P. D., & Chinapaw, M. J. M. (2019). Effects of physical activity interventions on cognitive and academic performance in children and adolescents: A novel combination of a systematic review and recommendations from an expert panel. *British Journal of Sports Medicine*, *53*(10), 640–647. https://doi.org/10.1136/bjsports-2017-098136

Smith, J., Eather, N., Morgan, P., Plotnikoff, R., Faigenbaum, A., & Lubans, D. (2014). The health benefits of muscular fitness for children and adolescents: A systematic review and meta-analysis. *Sports Medicine*, *44*(9), 1209–1223. https://doi.org/10.1007/s40279-014-0196-4

Smith, J. J., Eather, N., Morgan, P. J., Plotnikoff, R. C., Faigenbaum, A. D., & Lubans, D. R. (2014). The health benefits of muscular fitness for children and adolescents: A systematic review and meta-analysis. *Sports Medicine*, *44*(9), 1209–1223. https://doi.org/10.1007/s40279-014-0196-4

Soga, K., Masaki, H., Gerber, M., & Ludyga, S. (2018). Acute and long-term effects of resistance training on executive function. *Journal of Cognitive Enhancement*, *2*(2), 200–207. https://doi.org/10.1007/s41465-018-0079-y

Solis-Urra, P., Sanchez-Martinez, J., Olivares-Arancibia, J., Castro Pinero, J., Sadarangani, K. P., Ferrari, G., Rodríguez-Rodríguez, F., Gaya, A., Fochesatto, C. F., & Cristi-Montero, C. (2021). Physical fitness and its association with cognitive performance in Chilean schoolchildren: The Cogni-Action project. *Scandinavian Journal of Medicine & Science in Sports*, *31*(6), 1352–1362. https://doi.org/10.1111/sms.13945

Spanou, M., Kaioglou, V., Pesce, C., Mavilidi, M. F., & Venetsanou, F. (2022). “Move” their brain: Motor competence mediates the relationship of physical activity and executive functions in children. *Applied Sciences*, *12*(20), 10527. https://doi.org/10.3390/app122010527

Stillman, C. M., Cohen, J., Lehman, M. E., & Erickson, K. I. (2016). Mediators of physical activity on neurocognitive function: A review at multiple levels of analysis. *Frontiers in Human Neuroscience*, *10*, 626. https://doi.org/10.3389/fnhum.2016.00626

Stimpson, N. J., Davison, G., & Javadi, A.-H. (2018). Joggin’the noggin: Towards a physiological understanding of exercise-induced cognitive benefits. *Neuroscience & Biobehavioral Reviews*, *88*, 177–186. https://doi.org/10.1016/j.neubiorev.2018.03.018

Tomporowski, P. D., & Pesce, C. (2019). Exercise, sports, and performance arts benefit cognition via a common process. *Psychological Bulletin*, *145*(9), 929. https://doi.org/10.1037/bul0000200

Tucker, L. R., & Lewis, C. (1973). A reliability coefficient for maximum likelihood factor analysis. *Psychometrika*, *38*(1), 1–10. https://doi.org/10.1007/BF02291170

Van Waelvelde, H., Vanden Wyngaert, K., Mariën, T., Baeyens, D., & Calders, P. (2020). The relation between children’s aerobic fitness and executive functions: A systematic review. *Infant and Child Development*, *29*(3). https://doi.org/10.1002/icd.2163

Vazou, S., Klesel, B., Lakes, K. D., & Smiley, A. (2020). Rhythmic physical activity intervention: Exploring feasibility and effectiveness in improving motor and executive function skills in children. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.556249

Visier-Alfonso, M. E., Álvarez-Bueno, C., Sánchez-López, M., Cavero-Redondo, I., Martínez-Hortelano, J. A., Nieto-López, M., & Martínez-Vizcaíno, V. (2021). Fitness and executive function as mediators between physical activity and academic achievement: Mediators between physical activity and academic achievement. *Journal of Sports Sciences*, *39*(14), 1576–1584. https://doi.org/10.1080/02640414.2021.1886665

Wade, L., Beauchamp, M. R., Nathan, N., Smith, J. J., Leahy, A. A., Kennedy, S. G., Boyer, J., Bao, R., Diallo, T. M., Vidal-Conti, J., & Lubans, D. R. (2023). Investigating the direct and indirect effects of a school-based leadership program for primary school students: Rationale and study protocol for the ‘learning to Lead’cluster randomised controlled trial. *PLOS ONE*, *18*(1), e0279661. https://doi.org/10.1371/journal.pone.0279661

Webster, E. K., & Ulrich, D. A. (2017). Evaluation of the psychometric properties of the test of gross motor development—third edition. *Journal of Motor Learning and Development*, *5*(1), 45–58. https://doi.org/10.1123/jmld.2016-0003

Weintraub, S., Dikmen, S. S., Heaton, R. K., Tulsky, D. S., Zelazo, P. D., Bauer, P. J., Carlozzi, N. E., Slotkin, J., Blitz, D., Wallner-Allen, K., Fox, N. A., Beaumont, J. L., Mungas, D., Nowinski, C. J., Richler, J., Deocampo, J. A., Anderson, J. E., Manly, J. J., &Witt, E. (2013). Cognition assessment using the NIH toolbox. *Neurology*, *80*(11_supplement_3), S54–S64. https://doi.org/10.1212/WNL.0b013e3182872ded

Willoughby, M. T., & Hudson, K. (2023). Contributions of motor skill development and physical activity to the ontogeny of executive function skills in early childhood. *Developmental Review*, *70*, 101102. https://doi.org/10.1016/j.dr.2023.101102

Xue, Y., Yang, Y., & Huang, T. (2019). Effects of chronic exercise interventions on executive function among children and adolescents: A systematic review with meta-analysis. *British Journal of Sports Medicine*, *53*(22), 1397–1404. https://doi.org/10.1136/bjsports-2018-099825

Yang, Y., Shields, G. S., Zhang, Y., Wu, H., Chen, H., & Romer, A. L. (2022). Child executive function and future externalizing and internalizing problems: A meta-analysis of prospective longitudinal studies. *Clinical Psychology Review*, *97*, 102194. https://doi.org/10.1016/j.cpr.2022.102194

Yangüez, M., Bediou, B., Hillman, C. H., Bavelier, D., & Chanal, J. (2021). The indirect role of executive functions on the relationship between cardiorespiratory fitness and school grades. *Medicine & Science in Sports and Exercise*, *53*(8), 1656. https://doi.org/10.1249/MSS.0000000000002630

Zelazo, P. D. (2020). Executive function and psychopathology: A neurodevelopmental perspective. *Annual Review of Clinical Psychology*, *16*(1), 431–454. https://doi.org/10.1146/annurev-clinpsy-072319-024242

Zeng, Q., Hu, X., & Wang, Y. (2023). The association between muscle strength and executive function in children and adolescents: Based on survey evidence in rural areas of China. *Frontiers in Psychology*, *13*, 13. https://doi.org/10.3389/fpsyg.2022.1090143