Are Strength, Cardiorespiratory Fitness, and Motor Coordination Associated With Executive Functions Among Children Aged 6–10 Years?

¿La fuerza, la aptitud cardiorrespiratoria y la coordinación motora se asocian con las funciones ejecutivas en niños de 6 a 10 años?

Received: November 18, 2022; **Reviewed:** April 4, 2024; **Accepted:** July 31, 2026

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Abstract

The purpose of the study was to examine the associations among motor coordination, cardiorespiratory fitness, musculoskeletal performance, and attention and executive functions in children. A total of 271 children aged 6–10 years participated in the study. Motor coordination was evaluated using the *Körperkoordinationstest für Kinder*; cardiorespiratory fitness using the Yo-Yo Intermittent Recovery Test Level 1 adapted for children; and musculoskeletal fitness using the countermovement jump and squat jump tests. Attention and executive function were evaluated by the cancellation and the trail-making tests, parts A and B. Results showed that children with high and very high motor coordination exhibited higher executive functions than children with low motor coordination ($p < .05$), and those with high motor coordination had 1.12 to 18.8 times higher odds of achieving high and very high performance across executive function outcomes. Musculoskeletal fitness was inversely associated with executive function. Overall, motor coordination had the strongest association with executive function, while cardiorespiratory fitness showed a weaker association.

Keywords

Psychomotor performance; physical fitness; muscle strength; executive function; child.

Resumen

El objetivo del estudio fue verificar la asociación entre la coordinación motora, la aptitud cardiorrespiratoria y musculoesquelética, la atención y las funciones ejecutivas en niños. Participaron 271 niños de 6 a 10 años en el estudio. La coordinación motora se evaluó mediante el *Körperkoordinationstest für Kinder*; la aptitud cardiorrespiratoria, mediante la prueba Yo-Yo de recuperación intermitente, nivel 1, adaptada para niños; y la aptitud musculoesquelética, mediante pruebas de contramovimiento y de salto en cuclillas. La atención y las funciones ejecutivas se evaluaron mediante el test de cancelación y el test de trail, parte A y B. Los resultados mostraron que los niños con coordinación motora alta y muy alta presentaron mejores funciones ejecutivas que los niños con baja coordinación motora ($P < 0,05$), y aquellos con alta coordinación motora presentaron entre 1,12 y 18,8 veces mayores probabilidades de alcanzar un rendimiento alto y muy alto en los resultados de las funciones ejecutivas. La aptitud musculoesquelética mostró una asociación inversa con la función ejecutiva. En general, la coordinación motora presentó la asociación más fuerte con la función ejecutiva, mientras que la aptitud cardiorrespiratoria mostró una asociación más débil.

Palabras clave

Rendimiento psicomotor; aptitud física; fuerza muscular; función ejecutiva; niño.

How to cite [APA]:

Mazzoccante, R., Corrêa, H. de L., Sousa, I., Robert, W., Santana, F. S. de, Cattuzzo, M. T., Fukuda, C. C., Lima, P. da S., & Melo, G. F. de (2026). Are Strength, Cardiorespiratory Fitness, and Motor Coordination Associated With Executive Functions Among Children Aged 6–10 Years? *Acta Colombiana de Psicología*, 29, 1–18. https://doi.org/10.14718/ACP.2026.29.16

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Authors' Notes:

Acknowledgments. The authors thank the participating children, their parents or legal guardians, the school administrators, and the professionals and research assistants who contributed to participant recruitment, data collection, and assessment procedures.

Conflict of Interest Statement. The authors declare that they have no conflicts of interest related to the research, authorship, or publication of this article.

Funding. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data and Materials Availability. The dataset and analytical materials supporting the findings of this study are available from the corresponding author upon reasonable request. Access may be subject to ethical and confidentiality restrictions because the study involved children.

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Introduction

Human beings are directly impacted by a multitude of factors in their interactions with the environment (Andrades-Suárez *et al.*, 2022; Diamond, 2000; García Cantó *et al.*, 2021). The significant relationships between the individual and the environment determine their degree of development, especially in the cognitive domain (Diamond, 2000, 2007; García Cantó *et al.*, 2021; Hillman *et al.*, 2017). This condition is frequently observed in the interaction of physical exercise with executive functions (EFs), a crucial component for well-being and a healthy life (Diamond, 2007).

Recent research has demonstrated that physical exercise offers benefits beyond the physical and motor domains, including positive effects on cognitive development and expressive benefits in childhood and adolescence (Erickson *et al.*, 2015; Koutsandréou *et al.*, 2016; Santana *et al.*, 2017). Higher levels of cardiorespiratory fitness (CF) and motor coordination (MC) in children have been associated with better executive control and greater functional connectivity in brain regions involved in executive functioning (Hillman *et al.*, 2014; Luz *et al.*, 2015; Mazzoccante *et al.*, 2020). Executive control underpins the human capacity for self-regulation and affects social and academic life (Erickson *et al.*, 2015; MacDonald *et al.*, 2016; Torrijos-Niño *et al.*, 2014). The same relationship has not been demonstrated between increased strength and improvements in executive and academic functions. The influence of strength on EF in childhood remains inconclusive (Mazzoccante *et al.*, 2020; Santana *et al.*, 2017).

Proper functioning of EF is essential for children's and adolescents' development because it involves brain regions that control attention, thoughts, emotions, and actions (Diamond, 2012; Erickson *et al.*, 2015; Ishihara *et al.*, 2017). EF is divided into three components: (a) inhibitory control, responsible for the self-control and discipline needed to perform and/or complete a task; (b) working memory, responsible for maintaining and working with current and new information and reordering the information acquired; and (c) cognitive flexibility, defined as the ability to reflect on concepts to adapt to new demands or priorities, and fundamental processes for good social and school development (Diamond, 2012; Whedon *et al.*, 2016).

Diamond and Lee (2011) listed the following positive interventions in EF: computerized training, non-computerized games, aerobics, martial arts, yoga, mindfulness, and school curricula. The impact of physical exercise models in childhood and adolescence is not the same as in adult life (Güngör, 2014; Ishihara *et al.*, 2017; Kamijo *et al.*, 2016; O'Halloran *et al.*, 2011). During childhood and adolescence, the most expressive findings are related to the intervention of physical exercise in conjunction with complex motor activities; that is, activities that require cognitive control for the execution of movement (Güngör, 2014; Ishihara *et al.*, 2017; Kamijo *et al.*, 2016; O'Halloran *et al.*, 2011).

The development of CF and motor skills has an interesting influence on EF performance, contributing to body weight control (Diamond, 2000; Kamijo *et al.*, 2014; Reinert *et al.*, 2013). Positive effects on working memory were observed after 10 weeks of motor and cardiovascular exercise in children aged 9 to 10 years, with more pronounced results for the motor exercise intervention (Koutsandréou *et al.*, 2016).

Children with greater motor stimulation throughout their development will obtain better cognitive skills compared to children with lesser motor stimuli (Diamond, 2000; Hillman *et al.*, 2014; Resaland *et al.*, 2016; Rosenberg, 2015). The observation of intervention models has shown that the benefits of physical exercise in childhood are linked to activities with a focus on motor development, and complex activities with new or diverse MC components provide benefits to CF and EF (Diamond, 2000; Hillman *et al.*, 2014; Resaland *et al.*, 2016; Rosenberg, 2015).

The determination of which components of health-related physical fitness influence EF will allow for the development of intervention strategies (Diamond, 2000; Kamijo *et al.*, 2014; Mazzoccante *et al.*, 2020; Reinert *et al.*, 2013). Apparently, this interference occurs when both CF and MC are improved (Diamond, 2000; Kamijo *et al.*, 2014; Mazzoccante *et al.*, 2020; Reinert *et al.*, 2013). However, the association between EF and muscle strength remains controversial. In addition, few studies have addressed the interaction of these variables with EF and its prediction (Koutsandréou *et al.*, 2016).

Such knowledge may provide opportunities for professionals working with motor development to intervene more successfully, engaging practitioners across all stages of life. However, the predictive capacity of these variables for attention performance and EF in children still requires further research. Therefore, this study examined the associations between MC, CF, and musculoskeletal fitness and attention, cognitive flexibility, cognitive processing speed, and EF in children.

Methods

Study Design

This study used a cross-sectional, inferential design with a non-probabilistic, purposively selected sample and a descriptive-correlational approach (Pereira, 2011).

Sample

The study population consisted of 271 children with typical development aged 6 to 10 years (7.52 ± 1.5 years; boys = 45.75%) from Distrito Federal, Brazil. Sampling was non-probabilistic and purposive; participants and study sites were selected based on convenience. The researchers recruited participants through verbal invitation, with support from school principals. Prior to participation, all parents and/or legal guardians provided written informed consent, and all participating children provided written assent, ensuring voluntary, informed, and age-appropriate participation. Participants and their guardians were informed about the objectives, procedures, potential benefits, and risks.

Ethical Aspects

All procedures were conducted in accordance with internationally recognized ethical standards for research involving human participants and with Resolution No. 466/2012 of the Brazilian National Health Council. The study was approved by the Research Ethics Committee of Centro Universitário Euro-Americano (UNIEURO), Brazil (CAAE No. 36570020.0.0000.5056; Ethics Committee Opinion No. 4.274.829). Written informed consent was obtained from the parents or legal guardians, and assent was obtained from the children prior to their participation. Participant anonymity and confidentiality were ensured throughout the study.

The study was classified as low risk in the informed consent documentation. The foreseeable risks were those inherent to the assessment procedures, particularly the possibility of falls, fatigue, and minor musculoskeletal or orthopedic events during physical and motor tests. Preventive measures were adopted to minimize these risks, including conducting assessments in appropriate, safe environments and ensuring all procedures were administered by trained evaluators.

This study is part of the broader research project entitled "The Influence of Motor Coordination and Cardiorespiratory Fitness on Attention and Executive Function in Children and Adolescents" (*A influência da coordenação motora e aptidão cardiorrespiratória sobre a atenção e função executiva em crianças e adolescentes*). The primary objective of the broader project was to analyze the relationship of body composition, MC, muscular strength, and CF with attention and EFs in children and adolescents.

Procedure

All professionals who administered the tests were trained in advance. The children were familiarized with all instruments one week before the assessments. A trained interviewer conducted the anamnesis to ensure that the study's inclusion criteria were met.

After the anamnesis, the assessments were organized into three blocks: A) the Attentional Cancellation Test, used to assess selective attention, and the Trail Making Test parts A and B, used to assess sustained attention and cognitive flexibility, respectively; B) the jumping tests, used to assess strength performance, and the Yo-Yo Intermittent Recovery Test Level 1, used to assess CF; and C) anthropometric and body

composition assessments and the *Körperkoordinationstest für Kinder* (KTK), used to assess MC.

The order of the three assessment blocks was randomized separately for each school class by a simple draw. Only the order of the blocks was randomized, while the sequence of the tests within each block remained fixed. Assessments in each block were conducted on different days, with at least 1 week between consecutive blocks for each class. All assessments were conducted during the regular class period, either in a classroom or on the school's multisport court, depending on each test's characteristics and space requirements.

Within Block A, the Attentional Cancellation Test was administered first, followed by the Trail Making Test Parts A and B. Within Block B, the jumping tests were administered before the Yo-Yo Intermittent Recovery Test Level 1. Within Block C, the anthropometric and body composition assessments were performed before the KTK. Standardized instructions were provided to the children before each test.

EF was calculated as the mean of the standardized scores from the Attentional Cancellation Test and the Trail Making Test (Parts A and B), following Seabra and Dias (2012). The children had completed the same battery of tests six months prior to the assessments. Although previous exposure to the tests may induce a learning effect, all participants underwent comparable familiarization, reducing potential systematic bias. These instruments are suitable for repeated assessments during childhood and remain sensitive to individual differences. Nevertheless, a residual practice effect cannot be entirely excluded.

Instruments

Cardiorespiratory Fitness Test

CF was tested using the Yo-Yo test, which consists of sequences of runs with a rhythm controlled by sounds from a CD player. The run distances were 16 and 20 meters, respectively, for 6–9- and over-9-year-old children, with a track width of 1.3 meters (Ahler *et al.*, 2012; Andersen *et al.*, 2008). The rhythm was progressively increased with a 10-second rest interval. The finish was determined when the volunteer failed to reach 16 or 20 meters. To ensure performance at the speeds corresponding to each stage, one of the raters participated in the test to maintain the ideal pace, and capacity was determined by meters traveled.

Motor Coordination (Körperkoordinationstest Für Kinder)

MC was assessed with the KTK. The coordination capacity assessment was performed using the Motor Quotient (MQ), derived from the gross values obtained in each KTK task, and its summation resulted in the total MQ classified into five MC levels based on the total score (very high, high, normal, insufficient, and disturbance in global MC (Mazzoccante *et al.*, 2019; Mazzoccante *et al.*, 2020; Moreira *et al.*, 2019; Ré *et al.*, 2018).

This test is composed of four subtests: 1) walking backward along balance beams of different widths; 2) hopping for height; 3) jumping sideways over a slat; and 4) moving sideways on boards, as described elsewhere (Gorla *et al.*, 2009; Huyben *et al.*, 2016). Scores per subtest were converted into standardized MQs based on normative data (Gorla *et al.*, 2009). These standardized scores were adjusted for age (all subtests) and gender (hopping for height and jumping sideways over a slat). The MQs from all four subtests were then summed to obtain a total MQ score.

Strength Performance (Jumping Vertically)

Strength performance was measured using the Countermovement Jump and the Squat Jump (knees at 90 degrees), both initiated with the feet in a parallel position. Vertical jumping performance was determined in centimeters and evaluated according to the descriptions of the Bosco protocols (Bosco, 2002).

Anthropometric and Body Composition

The anthropometric and body composition assessment was based on body mass and height. The equations are as follows: Body Mass Index (BMI) = body weight (kg) / height² (m) (Petroski & Pires Neto, 1995). To interpret BMI values, the World Health Organization (WHO) growth percentile charts were used (de Onis *et al.*, 2007). Nutritional status by age was classified using the WHO cutoff points, in accordance with the recommendations of the Brazilian Society of Pediatrics

(BSP). Participants were allocated into two analytical groups: Group 1—eutrophic, with BMI values between the 3rd and 85th percentiles, and Group 2—children with excess weight, including those classified as overweight or obese, defined by BMI values at or above the 85th percentile. The classification used sex-specific percentile curves, accounting for differences in boys' and girls' growth and development.

Attention Cancellation Test (Selective Attention)

The attention cancellation test was performed as described by Montiel and Capovilla (2008). The test consists of three tasks, with one minute per task. Using paper and pencil, the children must scratch all figures related to another previously determined one (Seabra & Dias, 2012).

The tests were evaluated according to the total number of correct answers, as described by Seabra and Dias (2012). The test was already applied to Brazilian children in many different studies, presenting an adequate form to assess the instruments and is adequate to assess the EF components (Almeida *et al.*, 2018; Capovilla & Dias, 2008; Carvalho *et al.*, 2020; Fonseca *et al.*, 2015).

Trail Making Test, Parts A And B (Sustained Attention [Trail A]; Cognitive Flexibility [Trail B]; Cognitive Processing Speed [Trail B-A])

The Trail Making Test is a pencil-and-paper instrument divided into Parts A and B and containing letters and numbers. Part A consists of two sheets, one for linking numbers (1–12) in increasing numerical order and the other for linking letters (A–L) in increasing alphabetical order. Part B consists of a sheet with letters and numbers randomly arranged. The task consists of connecting letters and numbers alternately, in numerical and alphabetical order. One minute was allowed for each test (Almeida *et al.*, 2018; Capovilla & Dias, 2008; Carvalho *et al.*, 2020; Fonseca *et al.*, 2015; Seabra & Dias, 2012). The Trail Making A classification was categorized by the sum of the letter and number results. Part B was followed by a sequence of correct answers. Finally, the difference between the B-A tracks' results was calculated. All analyses were conducted according to the criteria adopted by Seabra and Dias (2012) and categorized by age.

Statistical Analysis

Descriptive statistics, including means and standard deviations, were calculated. Data normality was assessed with the Shapiro-Wilk test (Razali & Wah, 2011; Royston, 1982, 1995). Musculoskeletal, CF, and MC levels were categorized into the following levels based on each variable's percentiles: very low, low, average, high, and very high. Accordingly, we used a one-way analysis of variance with a Sidak post hoc test to test for differences in the cognitive variables among the strength, CF, and MC levels. Given the limitations of BMI as an indicator of body composition in children, we used median-based stratification as an exploratory analytical approach. Although BMI was descriptively classified using WHO percentiles, we dichotomized BMI and the other study variables (cardiorespiratory and muscular fitness, MC) at the median to allow homogeneous comparisons with EF and attention outcomes. This procedure was not intended as a clinical classification.

Bivariate and multivariate regression models were used to calculate odds ratios (ORs). In addition, Pearson's linear correlation test was applied to assess correlations between the indicators and attention and EF. The study used a significance level of $p \leq .05$.

A path diagram analysis was specified based on relationships reported in the literature and used as a theoretical framework for examining the associations of body composition and physical and motor variables with attention and EF. Given the study's cross-sectional design, the path coefficients were interpreted as associations and did not imply causal relationships. The sample size was considered adequate based on the commonly recommended ratio of at least 5–10 participants per freely estimated parameter. Model fit was evaluated using the chi-square test, for which a nonsignificant result, $p(\chi^2) \geq .05$, was considered indicative of adequate fit; the comparative fit index (CFI), with values ≥.95 indicating good fit; the Tucker–Lewis index (TLI), with values ≥.90 indicating acceptable fit and values ≥.95 indicating good fit; the root mean square error of approximation (RMSEA), with values ≤.08 indicating acceptable fit; and the standardized root mean square residual (SRMR), with values ≤.08 indicating acceptable fit (Hu & Bentler, 1999). The model showed an acceptable overall fit: $\chi^2(19) = 20.85$, $p = .345$, CFI = .96, TLI = .94, RMSEA = .02, and SRMR = .03. Although the

TLI value did not reach the more stringent criterion of .95, it exceeded .90 and was therefore interpreted as indicating acceptable fit. The analyses were performed using Stata version 13.0, GraphPad Prism version 8.0, and the Statistical Package for the Social Sciences version 22.0.

Results

All participants completed the assessment protocol without any adverse events, interference, or physical injury during data collection. Table 1 presents the results for anthropometric characteristics, physical fitness, and EF.

Table 1. Sample Anthropometric Characteristics, Physical Fitness, and Executive Function of School Children

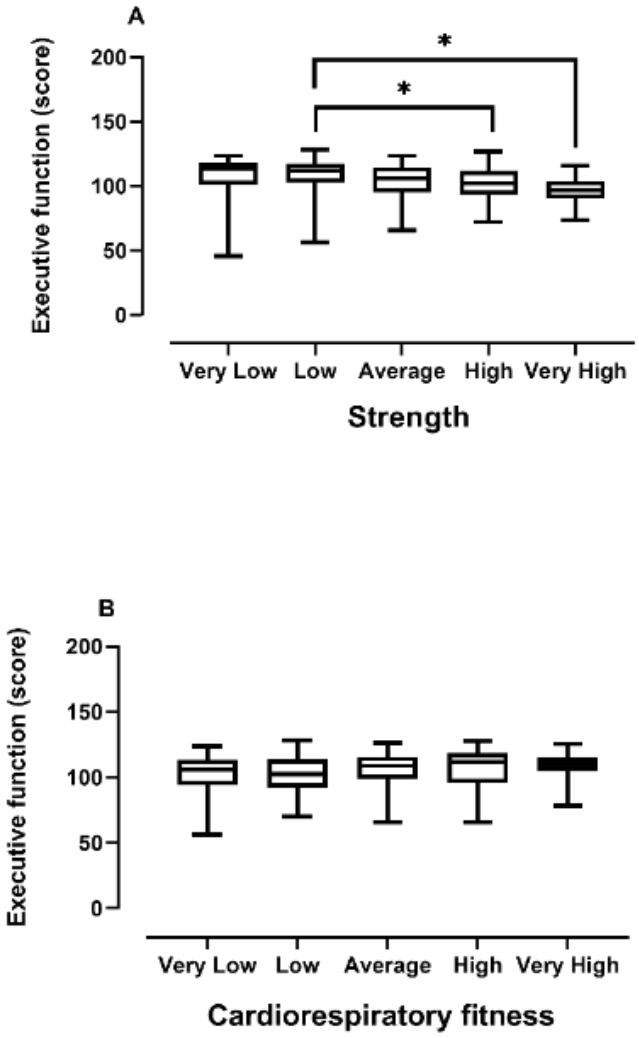
Variables	*Mean ± SD*
Age (years)	7.52 ± 1.5
Sample anthropometric characteristics	
Body weight (kg)	27.3 ± 7.9
Height (m)	1.27 ± 0.11
BMI ($kg.m^{2(-1)}$)	16.7 ± 2.7
Eutrophic	205 (75.65%)
Overweight and obesity	66 (24.35%)
Physical fitness outcomes	
Strength (cm)	18.4 ± 3.8
Cardiorespiratory fitness (m)	303.6 ± 206.18
Motor coordination (score)	82.4 ± 16.27
Executive function outcomes	
Selective attention (score)	107.7 ± 18.7
Sustained attention (score)	97.28 ± 23.82
Cognitive flexibility (score)	108.9 ± 17.6
Cognitive processing speed (score)	109.3 ± 15.7
Executive function (score)	104.6 ± 13.7

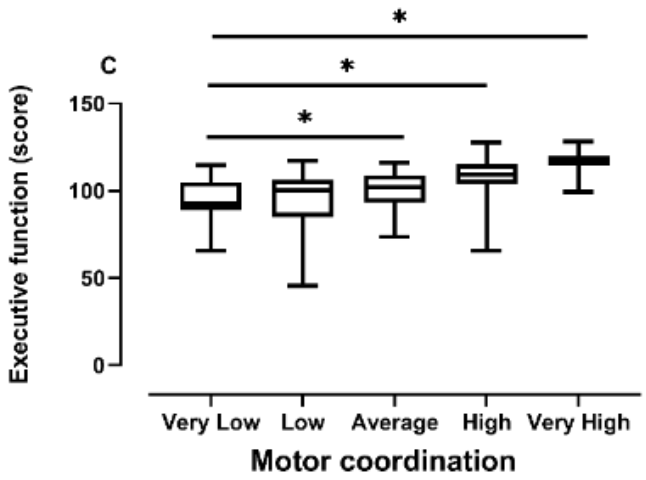
Note. Group 1 – eutrophic, with BMI values between the 3rd and 85th percentiles; and Group 2 – children with excess weight, including those classified as overweight and obese, defined by BMI values at or above the 85th percentile.

Children with high and very high strength exhibited lower EF compared to children with low strength ($p < .05$). No difference in EF according to the percentiles of cardiorespiratory levels was observed ($p > .05$). Children with average, high, and very high MC presented with higher EF than children with low MC ($p < .05$). Also, the high MC percentile demonstrated better EF in relation to the very low and average percentile ($p < .05$). Very high MC showed higher EF than the very low, average, and high percentiles ($p < .05$) (Figure 1).

The values for the percentiles were as follows: strength—very low (7.25 to 12.41), low (12.76 to 18.18), average (18.2 to 20.05), high (20.07 to 24.08), very high (24.3 to 31.38); CF—very low (80 to 128), low (160 to 252), average (256 to 326), high (352 to 560), very high (576 to 1344); MC—very low (46 to 57), low (58 to 70); average (71 to 80); high (81 to 96), very high (97 to 118).

Figure 1. EF According to Strength (A), Cardiorespiratory Fitness (B), and Motor Coordination (C) Levels





Note. This figure compares EF values across percentile classifications—very low, low, moderate, high, and very high—for physical and motor variables.
* $p < .05$

Table 2 presents the ORs for physical fitness and the components of EF.

Higher musculoskeletal fitness was associated with lower odds of high performance in selective attention (*OR* = 0.44, 95% CI [0.27, 0.73]), cognitive flexibility (OR = 0.26, 95% CI [0.16, 0.45]), cognitive processing speed (*OR* = 0.40, 95% CI [0.24, 0.66]), and overall EF (*OR* = 0.28, 95% CI [0.15, 0.51]). No significant association was observed for sustained attention. High CF was associated with 1.96- and 1.80-fold higher odds of achieving high performance in selective attention and EF, respectively.

Table 2. Odds Ratios for High and Low Physical and Motor Indicators in Relation to Attention and Executive Function Outcomes

Variables		Median values	Executive function test		*OR* (95% CI)
			≥115 scores	<115 scores	
BMI	Selective attention (score)	High	47	89	0.47 (0.29–0.77)*
		Low	71	64	
	Sustained attention (score)	High	14	122	0.99 (0.45–2.16)
		Low	14	121	
	Cognitive flexibility (score)	High	39	97	0.43 (0.26–0.71)*
		Low	65	70	
	Cognitive processing speed (score)	High	42	94	0.55 (0.34–0.91)*
		Low	60	75	
	Executive function (score)	High	25	111	0.43 (0.24–0.76)*
		Low	46	89	

» Table 2. (continued)

» Table 2. (continued)

Variables		Median values	Executive function test		*OR* (95% CI)
			≥115 scores	<115 scores	
Musculoskeletal fitness	Selective attention (score)	High	46	90	0.44 (0.27–0.73)*
		Low	72	63	
	Sustained attention (score)	High	15	121	1.16 (0.53–2.54)
		Low	13	122	
	Cognitive flexibility (score)	High	32	104	0.26 (0.16–0.45)*
		Low	72	63	
	Cognitive processing speed (score)	High	37	99	0.40 (0.24–0.66)*
		Low	72	63	
	Executive function (score)	High	20	116	0.28 (0.15–0.51)*
		Low	51	84	
Cardiorespiratory fitness	Selective attention (score)	High	75	72	1.96 (1.20–3.20)*
		Low	43	81	
	Sustained attention (score)	High	12	135	0.60 (0.27–1.32)
		Low	16	108	
	Cognitive flexibility (score)	High	63	84	1.51 (0.92–2.49)
		Low	41	83	
	Cognitive processing speed (score)	High	59	88	1.26 (0.76–2.07)
		Low	43	81	
	Executive function (score)	High	46	101	1.80 (1.03–3.15)*
		Low	25	99	
Motor coordination	Selective attention (score)	High	75	72	2.30 (1.42–3.82)*
		Low	43	81	
	Sustained attention (score)	High	12	135	1.12 (0.51–2.46)
		Low	16	108	
	Cognitive flexibility (score)	High	63	84	6.87 (3.87–11.93)*
		Low	41	83	
	Cognitive processing speed (score)	High	59	88	5.04 (2.92–8.69)*
		Low	43	81	
	Executive function (score)	High	65	73	18.8 (7.78–45.68)*
			6	127	

Note. Median values: BMI (high ≥15.97 kg/m^2 and low ≤15.96 kg/m^2); strength (high >18.23 cm and low ≤18.22 cm); CF (high ≥256 m and low ≤255.99 m); MC (high ≥80 and low ≤79.99).
* Significant values according to CI.

Figure 2 describes the explanatory model using the path diagram method for selective attention, cognitive flexibility, and cognitive processing speed. For selective attention, the model presented an explanatory factor of R^2 = .49 for the variables (MC: β = .29, CF: β = .07, BMI: β = -.13, strength: β = -.15); the cognitive flexibility model presented an explanatory factor of R^2 = .45 (MC: β = .55, CF: β = -.74, BMI: β = -.81, strength: β = -.25); and with MC mediating the BMI (β = -.44) and for cognitive processing speed, the model presented an explanatory factor of R^2 = .20 (MC: β = .40, CF: β = -.69, BMI: β = -.62, strength: β = -.20).

Figure 2. Path Diagram With Strength, Cardiorespiratory Fitness, and Motor Coordination as Predictors of (A) Selective Attention, (B) Cognitive Flexibility, and (C) Cognitive Processing Speed

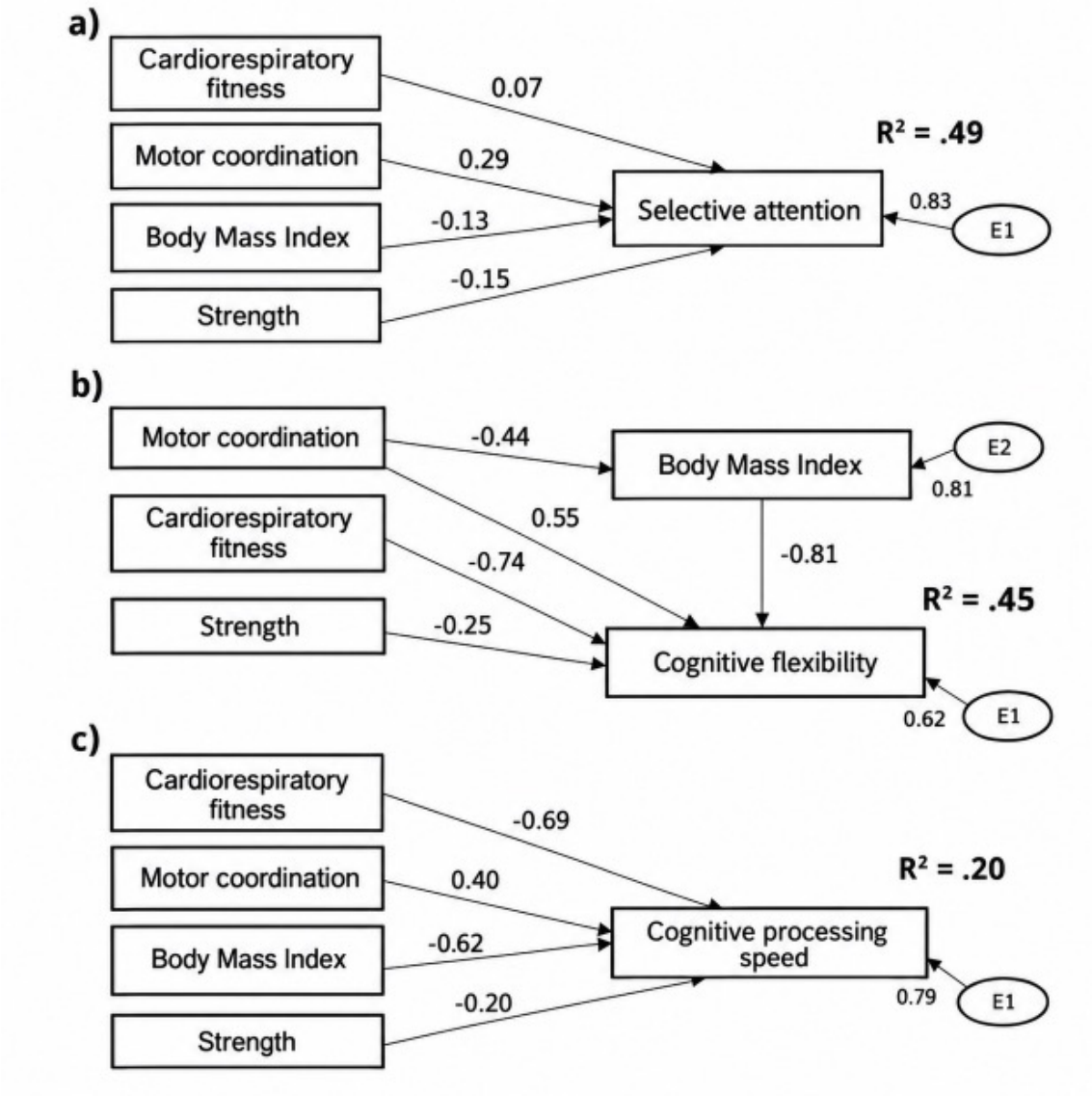
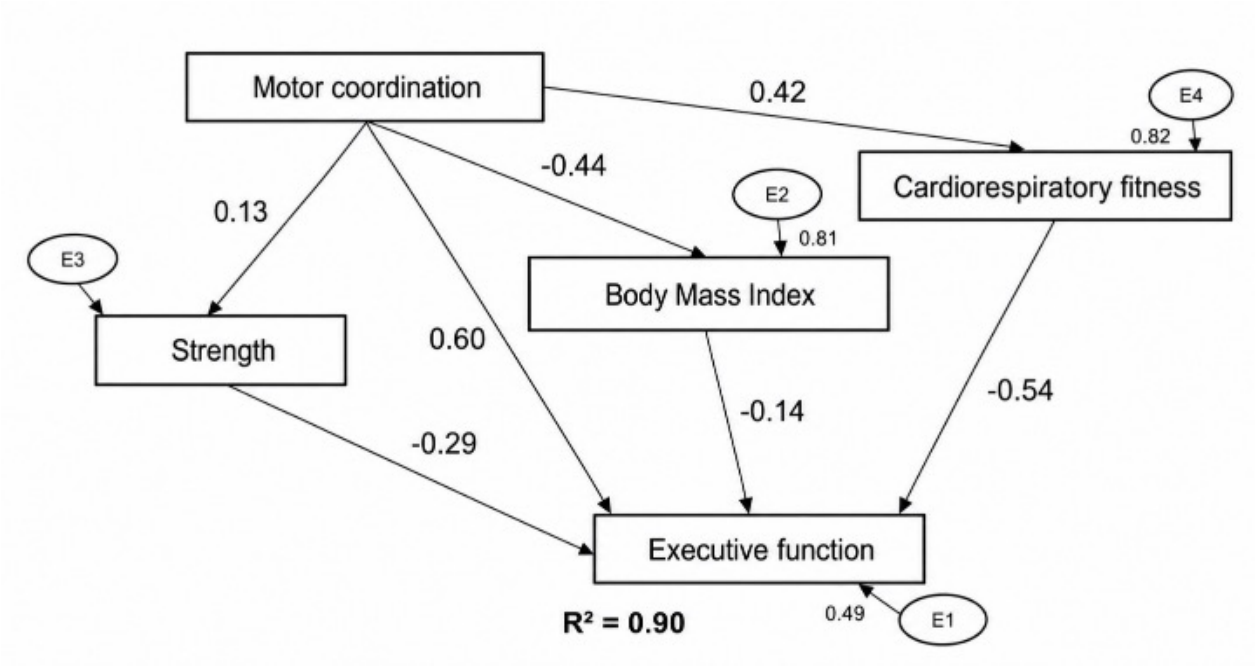


Figure 3 presents a path diagram for EF. The model showed an explanatory R^2 of .90 when examining the direct association between the variables. The model presented these explanatory factors: MC: β = .60 and CF: β = -.54. The results when considering MC as an intermediary variable in the theoretical path model of the responses of CF, BMI, and strength are shown in Figure 3 (CF: β = .42, BMI: β = -.44, strength: β = .13). CF and strength were found to have a positive association.

Figure 3. Path Diagram With Strength, Cardiorespiratory Fitness, and Motor Coordination as Predictors of Executive Function



Discussion

The main results of this study demonstrated a strong correlation between MC and the attention and EF components. These findings are consistent with a recent systematic review and meta-analysis that identified a positive association between motor competence and EFs in children and adolescents (Bao *et al.*, 2024). More specifically, a recent study involving children aged 7–11 years found low-to-moderate associations between motor competence and inhibitory control, task-switching, and working memory. However, these associations varied across school grades, suggesting that developmental stage may influence the relationship between motor competence and specific EFs (Ludyga & Herrmann, 2025). On the other hand, CF appeared weakly correlated with those EFs. Moreover, the results on strength were mixed, limiting inferences about its relationship to attention and EF. Schmidt *et al.* (2017) observed the impact of strength, CF, and MC on EF and academic performance in children aged 10–12 years. They found that CF and strength were weakly related to EF; however, MC was positively related to EF. Similar results were also found by Resaland *et al.* (2016), who analyzed the effect of an increasing physical activity level on academic performance during a 7-month period in 10-year-old children (Resaland *et al.*, 2016). They found no impact on math test scores, reading fluency, or English comprehension. In contrast, Budde *et al.* (2008) observed that an acute intervention of complex motor exercises improved sustained attention in adolescents aged 13–16 years (Budde *et al.*, 2008). These findings are in line with this study.

The positive relationship between increased cardiovascular fitness and EF may result from increased cerebral blood flow and changes in the central nervous system's architecture (Erickson *et al.*, 2015; Luz *et al.*, 2015). Moreover, the motor tasks involved in exercise practice seem to be a determining factor in EF performance in children, as childhood is an extremely sensitive period for a child's acquisition and overall development. Children encounter activities that require top-down cognitive control, calling for cognitive processing and organization to accomplish the motor task. This will include stronger effects on all components of EF than exercises with low cognitive demands. This cognitive demand is present in games and sports. Also, the child's engagement in these activities is greater than in training with specialized exercises that require less movement diversity (Güngör, 2014; Kamijo *et al.*, 2016; MacDonald *et al.*, 2016).

The cerebellum regulates MC and is also linked to neuropsychological factors through its role in emotion and cognition. These conditions are mediated by neural interactions between the cerebellum and the hypothalamus and prefrontal cortex, which are responsible for emotional control and EF, respectively. Thus, the cerebellum helps regulate strength, rhythm, and frequency, and modulates motor tasks. Moreover, it regulates the speed, consistency, and adequacy of the cognitive and emotional processes involved in executing motor tasks (Diamond, 2000; Ishihara *et al.*, 2017; O'Halloran *et al.*, 2011). Hence, children involved in games and sports that require planning for open motor tasks develop a broad motor repertoire, which supports improvements in CF and strength (Ishihara *et al.*, 2017). Consequently, this improves EF performance, as observed in this study's results.

Physical exercise plays an important role in EF. This influence is more relevant to new and/or complex motor tasks that require greater cognitive and executive control (Kamijo *et al.*, 2016; Koutsandréou *et al.*, 2016; Mazzoccante *et al.*, 2020; Morales *et al.*, 2024). This process occurs because cognitive motor learning goes through three stages: cognitive, associative, and autonomous (Diamond, 2000; Erickson *et al.*, 2015; Oliveira *et al.*, 2013). The cognitive stage is initially characterized by the understanding of the movement. The second stage involves learning the movement, allowing the learner to use external information to improve execution. Finally, the third stage occurs because the movement has been consolidated and automated. Within these three stages, attentional, cognitive, and executive demands are higher at the beginning of learning and decrease as learning progresses (Diamond, 2000; Erickson *et al.*, 2015; Oliveira *et al.*, 2013). Thus, physical exercise aimed at improving executive and cognitive functions needs to be paired with a gradual increase in motor complexity (Assis *et al.*, 2018; Kamijo *et al.*, 2016; Koutsandréou *et al.*, 2016; Oliveira *et al.*, 2013).

In this regard, EFs need challenges to drive continuous improvement. Pesce *et al.* (2016) demonstrated the effect of physical education classes for 6 months, once a week, in children aged 9 and 10, with the prescription centered on the complexity of open motor tasks, including requirements for social interaction, problem solving, MC, and cognitive flexibility. They observed several improvements in inhibitory control, despite a reduced class frequency.

In contrast, BMI was associated with different responses in cardiorespiratory capacity and MC. Recent studies indicate that changes in body composition affect physical and cognitive health throughout a child's development. Da Costa *et al.* (2019) showed that children with a high BMI and fat percentage had lower inhibitory control in relation to eutrophic children (Bass & Eneli, 2015; Da Costa *et al.*, 2019; Kamijo *et al.*, 2012; Liang *et al.*, 2014). Within this worrying situation of overweight and obese children, physical exercise is shown to be a non-pharmacological treatment for this condition. As demonstrated by Esteban-Cornejo *et al.* (2017), CF plays an important role in the deleterious effects of overweight on children's brain health and school performance. This study also found that children with higher BMI had an inverse correlation ($\beta = -.81$) with cognitive flexibility performance, and this inverse association was reduced by almost half ($\beta = -.44$) when BMI was associated with higher MC regarding cognitive flexibility performance.

Physical fitness is a primary determinant of lifelong health and includes several aspects, such as strength, CF, and MC. However, motor competence development has been shown to benefit from greater EF capacity in children (Esteban-Cornejo *et al.*, 2017). This period is crucial for forming neural pathways because of children's high neural plasticity, which can be stimulated by the interplay between environmental interaction and motor tasks. Moreover, unnecessary connections are eliminated through a process called synaptic pruning; therefore, physical exercise throughout childhood and adolescence is particularly important (Leisman *et al.*, 2016).

This study has some limitations. First, its cross-sectional design does not allow for establishing causal relationships or determining the temporal direction of the observed associations. Second, the instruments used provide indirect measures of EF and do not directly assess neural activity. Categorizing continuous variables may also reduce statistical power, increase information loss, and limit the ability to identify more precise relationships among physical fitness, MC, and EF. Therefore, the results derived from the categorized variables should be interpreted with caution. In addition, the children's maturational status was not objectively assessed and may have influenced both MC and EF. Nevertheless, previous studies have reported associations of physical exercise and physical fitness

with cardiovascular, motor, and EF across different age groups (Chang *et al.*, 2011; Erickson *et al.*, 2015; Esteban-Cornejo *et al.*, 2017; Güngör, 2014; Hillman *et al.*, 2017; Kamijo *et al.*, 2016; Santana *et al.*, 2017).

On the other hand, the relationships presented in this study are highly relevant to the accumulation of scientific and social knowledge, given the lack of studies examining the relationship between children's physical fitness and EF. In addition, the instruments used in the study are easy for other researchers and professionals in the field to access and are widely used in research with children. However, some limitations should be acknowledged. Furthermore, body composition was estimated using BMI, which is known to present several limitations and potential biases in pediatric populations, particularly due to growth and maturation processes. Likewise, the EF measures employed are indirect assessments; although widely accepted and appropriate for research settings, they may not fully capture the complexity of executive functioning in children. Future longitudinal studies using more precise measures of body composition and comprehensive EF assessments are warranted to confirm and extend the findings reported here.

Conclusion

In this sample of children aged 6–10 years, EF was strongly associated with MC, while CF had a weaker association with EF. Musculoskeletal fitness was inversely associated with EF, although this finding should be interpreted with caution given the study's cross-sectional design. Strength and CF seem more closely related to MC than to cognitive responses, as higher MC was associated with better strength and CF.

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