

Cardiovascular fitness and executive functioning in primary school-aged children

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Abstract

Previous research in children has shown that higher cardiovascular fitness is related to better executive functioning. However, the available literature is hampered by methodological limitations. The present study investigates the relationship between cardiovascular fitness and executive functioning in a large sample of healthy children ($N = 814$). Cardiovascular fitness was assessed with estimated VO₂Max from 20 m Shuttle Run Test performance. Executive functioning was assessed using a set of computerized neurocognitive tasks aimed at executive functions (working memory, motor inhibition, interference control) and lower-level neurocognitive functions (information processing and attention). Dependent measures derived from the neurocognitive tests were subjected to principal component analysis. Mixed model analyses tested the relation between cardiovascular fitness and neurocognitive functioning components. Results showed that children with higher cardiovascular fitness performed better on the neurocognitive function components Information Processing and Control, Visuospatial Working Memory and Attention Efficiency. The following measures contained in these components contributed to the observed relations: information processing measures, visuospatial working memory, and speed of alerting attention. No relationship was found between cardiovascular fitness and the other components: Verbal Working Memory, Attention Accuracy, and Interference Control. The present study suggests that there is a relationship between cardiovascular fitness and a specific set of executive functions and lower level neurocognitive functions. These findings highlight the importance of cardiovascular fitness for the overall health of school-aged children.

KEYWORDS

children, executive functioning, fitness, information processing, inhibition, interference control

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1 | INTRODUCTION

A sedentary lifestyle during childhood is related to an increased prevalence of several chronic diseases across the life span, including cardiovascular disease and diabetes (Gabel et al., 2016; Tremblay et al., 2011). It is known that participation in the recommended 60 min per day of moderate-to-vigorous-intensity physical activity for children leads to a wide range of physical benefits, such as increased cardiovascular fitness and reduced risk of type 2 diabetes, reduced risks for cardiovascular disease and obesity, as well as better bone health and mental well-being (Janssen & LeBlanc, 2010). Moreover, recent evidence indicates that physical fitness, which refers to the ability to engage in physical activity for a protracted period of time (Rowland, 2007), is related to enhanced neurocognitive functioning in children (Chaddock-Heyman, Hillman, Cohen, & Kramer, 2014; De Bruijn, Hartman, Kostons, Visscher, & Bosker, 2018; Donnelly et al., 2016; Singh et al., 2019).

Several neural mechanisms have been identified through which physical fitness may be related to neurocognitive functioning. A single bout of physical activity directly promotes cerebral blood flow and upregulation of neurotransmitters (e.g., epinephrine, dopamine; Dishman et al., 2006; McAuley, Kramer, & Colcombe, 2004; Querido & Sheel, 2007), both facilitating neurocognitive processes. Prolonged moderate-to-vigorous-intensity physical activity results in increased cardiovascular fitness—an increase in the ability of the heart to deliver oxygen to muscles and other parts of the body (American College of Sports Medicine, 2013). Cardiovascular fitness thus reflects past physical activity levels (Rowland, 2007), although cardiovascular fitness is also strongly determined by genetic factors (Malina, Bouchard, & Bar-Or, 2004). Interestingly, higher levels of cardiovascular fitness are associated with an increased release of neurotrophic factors (e.g. brain-derived neurotrophic factor and neural growth factor) and with both increased neural blood vessel formation and neurogenesis (Colcombe et al., 2006; Dishman et al., 2006; Swain et al., 2003). These neural mechanisms are known to promote plasticity in the structure and function in brain areas that support neurocognitive functioning (Vaynman & Gomez-Pinilla, 2006).

Among the various domains of neurocognitive functioning, the current state of the literature suggests that attention, interference control, and working memory are the most relevant functions in relation to physical activity (Best, 2010; de Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018; Verburgh, Scherder, van Lange, & Oosterlaan, 2014). Executive functions such as interference control, inhibition, and working memory facilitate reasoning, problem solving, and planning (Collins & Koechlin, 2012; Zelazo & Müller, 2002). Lower level neurocognitive functions, such as attention and information processing, are considered prerequisites for these executive functions. Executive functions are important predictors of behavioral functioning, academic achievement, health, wealth and quality of life throughout (Diamond & Lee, 2011; Moffitt et al., 2011). The rapid proliferation of executive functioning during childhood and adolescence is thought to be the result of structural and functional

Research highlights

- This study assessed cardiovascular fitness and executive functioning in a group of children using a set of neurocognitive function measures aimed at executive functioning.
- We found relations between cardiovascular fitness and information processing measures, visuospatial working memory, and speed of alerting attention.
- No relations were found between cardiovascular fitness and verbal working memory, attention accuracy, and interference control.
- The previously reported relationship between cardiovascular fitness and both interference control and attention seems to reflect effects of cardiovascular fitness on information processing efficiency.

changes in the frontal lobes, including myelination, neurogenesis, and angiogenesis (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). A mature level of executive functioning is achieved in the late 20 s (De Luca et al., 2003). Regular physical activity during this developmental window may facilitate experience-dependent plasticity of brain structure and function, potentially stimulating maturation of executive functioning (Giedd et al., 1999).

Cross-sectional studies indicate a positive relation between cardiovascular fitness and executive function in children. Interference control (i.e. the ability to suppress irrelevant information, an aspect of inhibition) is one of the most investigated functions in relation to cardiovascular fitness. It has been shown that higher fit children outperform lower fit children on tasks of interference control, with larger differences between higher fit and lower fit children for task conditions that require greater amounts of inhibitory ability (Buck, Hillman, & Castelli, 2008; Chaddock et al., 2012; Hillman, Buck, Themanson, Pontifex, & Castelli, 2009; Kao et al., 2017; Pontifex, Scudder, Drollette, & Hillman, 2012; Pontifex et al., 2011; Wu et al., 2011). There is also evidence that higher fit children outperform their lower fit peers on working memory tasks (Drollette et al., 2016; Scudder et al., 2014), attention tasks (Syväoja, Tammelin, Ahonen, Kankaanpää, & Kantomaa, 2014), and planning tasks (Davis & Cooper, 2011).

Although ample research has been carried out on the association between cardiovascular fitness and executive functioning, the generalizability of the findings of these studies may be questioned. First, the great majority of the available studies have assessed one single aspect of executive functioning resulting in a fragmented view on isolated aspects of executive functioning (Buck et al., 2008; Chaddock et al., 2012; Kao et al., 2017; Pontifex et al., 2011). Second, the majority of studies used group comparisons between higher- and lower fit children and did not test the continuous relationship between cardiovascular fitness and executive functioning (Chaddock et al., 2012; Hillman et al., 2009; Kao et al., 2017;

Pontifex et al., 2011, 2012; Wu et al., 2011). Testing the continuous relationship would increase statistical power and would allow investigation of the presumed relation between cardiovascular fitness and executive functioning. To summarize, the available literature on the relationship between cardiovascular fitness and executive functioning has several methodological limitations, including single construct assessment and limited research designs.

The present study aims to investigate the relationship between cardiovascular fitness and executive functioning in a large and representative sample of healthy school-aged children, using a set of neurocognitive function measures aimed at executive functions (i.e. working memory, motor inhibition, interference control) and lower level neurocognitive functions (information processing and attention). It was hypothesized that higher levels of cardiovascular fitness would be associated with better executive functioning, in particular interference control. We also investigated whether the relationship between cardiovascular fitness and executive functioning was moderated by demographic characteristics such as age, sex, socio-economic status (SES), and participation in organized sports.

2 | METHODS

2.1 | Participants

Children in the third and fourth grade of 22 primary schools in the Netherlands were recruited during the school year of 2016–2017. Parents and/or guardians of 891 children gave written consent for participation of their child (in line with the Dutch law). To limit the chance that children did not understand the task instructions, children were excluded when they had an estimated IQ < 70 ($n = 10$; also see Measurements). Participating children were excluded from further analyses when they did not attend the cardiovascular fitness measurement ($n = 50$) or the neurocognitive assessment ($n = 17$). Table 1 shows the demographics of the participating children ($n = 814$, 7.44–11.14 years old). Overweight and obesity was observed in 12.4% and 3.0% of the participants, which parallels recent figures observed in the Dutch pediatric population (Cole & Lobstein, 2012; Volksgezondheid en zorg, 2018).

2.2 | Measurements

2.2.1 | Cardiovascular fitness

Cardiovascular fitness was assessed with the 20 m Shuttle Run Test (20 m SRT; Adam, Klissouras, Ravazzolo, Renson, & Tuxworth, 1988). During this test, children run back and forth on a 20-m track, and need to reach the other side of the track at or before an auditory signal. The timing of the auditory signal is initially set at a required average speed of 8 km/hr, and is manipulated each minute to increase the required speed by 0.5 km/hr at a time. The test was terminated when a child failed to reach the required distance in time on two consecutive

TABLE 1 Descriptive sample characteristics ($n = 814$)

	Mean (SD)	Range
Age, years	9.16 (0.65)	7.44–11.14
Sex, n girls (%)	407 (50.0%)	
BMI, kg/m ^{2a}	16.68 (2.31)	12.24–24.06
Healthy weight, n (%) [‡]	687 (84.6%)	
Overweight, n (%) [‡]	101 (12.4%)	
Obesity, n (%) ^b	24 (3.0%)	
Grade three, n (%)	417 (51.2%)	
Grade four, n (%)	397 (48.8%)	
IQ	101.27 (13.55)	71–152
SES ^c	4.49 (0.99)	0–7
Organized sport participation (min per week) ^d	145.91 (107.63)	0–1,080

Abbreviations: BMI, body-mass index; SES, socio-economic status.

^a $n = 812$.

^bAccording to the reference values by Cole and Lobstein (2012).

^cRange 0 (no education) to 7 (post-doctoral education).

^d $n = 745$.

crossings of the track. Cardiovascular fitness was determined as the number of completed trajectories (20 m), which has shown to be a reliable measure of cardiovascular fitness in children. From the last trajectory that was completed, the maximal oxygen uptake (VO₂max in ml kg⁻¹ min⁻¹) was estimated by using the following formula: $(31.025 + (3.238 \times \text{velocity}) - (3.248 \times \text{age}) + (0.1536 \times \text{age} \times \text{velocity}))$; Leger, Mercier, Gadoury, & Lambert, 1988).

2.2.2 | Neurocognitive functioning tasks

All neurocognitive tasks and corresponding outcome measures are listed in Table 2. All measures have established psychometric properties and have been used extensively in previous research (Königs et al., 2015; Verbruggen & Logan, 2009; Verburgh et al., 2014; Wechsler, 1991).

Attention Network Test

An adapted version of the Attention Network Test (ANT) was used to measure information processing, attention processes, and interference control (Fan et al., 2002; Rueda et al., 2004). Target stimuli consisting of an arrow pointing left or right were presented on a computer screen. Children were instructed to respond as quickly as possible to the direction of a target stimulus by pressing the corresponding button. The target stimuli were flanked by two distractors on each side, which could be neutral (flat lines without spatial information), congruent (identical arrows pointing to the same direction as the target), or incongruent (identical arrows pointing to the other direction than the target). Target stimuli were preceded by three types of warning cues—a central cue in the middle of the screen, a spatial cue indicating the position of

TABLE 2 Description and operationalization of neurocognitive measures

Task	Measures	Description	Dependent variable
ANT	Information processing	The speed of responding to target appearance	Mean reaction time (ms) on neutral trials
	Tau	Lapses of attention	The average of the exponential component of the fitted ex-Gaussian curve, reflecting the influence of extremely slow responses (lapses of attention) on information processing
	Alerting attention	The speed of achieving an alert state	The difference in mean reaction time (ms) between central cue trials and no cue trials
		The accuracy of achieving an alert state	The difference in percentage of correct responses on central cue trials and no cue trials
	Spatial attention	The speed of spatially orienting to information	The difference in mean reaction time (ms) between spatial cue trials and central cue trials
		The accuracy of spatially orienting to information	The difference in the percentage of correct responses on spatial cue trials and central cue trials
Interference control	The speed of suppressing irrelevant information	The difference in mean reaction time (ms) between incongruent trials and congruent trials	
	The accuracy of suppressing irrelevant information	The difference in the percentage of correct responses on incongruent trials and congruent trials	
DS	Verbal short-term memory	The ability to hold verbal information in short-term memory	The product of the number of correct responses and the highest span reached in the forward condition (Kessels, Van Zandvoort, Postma, Kappelle, & De Haan, 2000)
	Verbal working memory	The ability to manipulate verbal information in working memory	The product of the number of correct responses and the highest span reached in the backward condition (Kessels et al., 2000)
GT	Visuospatial short-term memory	The ability to hold visuospatial information in short-term memory	The product of the number of correct responses and the highest span reached in the forward condition (Kessels et al., 2000)
	Visuospatial working memory	The ability to manipulate visuospatial information in working memory	The product of the number of correct responses and the highest span reached in the backward condition (Kessels et al., 2000)
SST	Motor inhibition efficiency	The latency of an inhibitory process	The mean reaction time (ms) calculated for correct responses on go trials subtracted by the average stop signal delay time (ms)

Abbreviations: ANT, Attention Network Test; DS, Digit Span; GT, Grid Task; SST, Stop Signal task.

the upcoming target, or no cue. All trials were counterbalanced for cue condition, spatial cue location, stimulus condition, and stimulus location, and were presented in predefined random order. As lapses of attention cause extreme slow responses that inflate information processing speed, we used so-called ex-Gaussian modeling of reaction time distributions to calculate the contribution of extreme slow responses (i.e. lapses of attention, *tau*; Lacouture & Cousineau, 2008). Estimates of tau were obtained from fitting the ex-Gaussian distribution to the reaction times data in which tau represents the exponential component and characterizes the slow reaction times in the tail of the distribution. Background information on ex-Gaussian modeling and full explanation of the mathematical procedure is provided elsewhere (Lacouture & Cousineau, 2008; Van Zandt, 2000; Whelan, 2008).

Digit Span

The forward and backward condition of the Digit Span Task were used to measure verbal working memory (WISC-III; Wechsler, 1991).

Children were required to repeat a sequence of numbers presented auditorily by the examiner in the order of presentation (forward condition) or reversed order (backward condition). Trial difficulty was determined by length of the sequence, which increased with one digit every other trial. The task was terminated after two consecutive incorrect responses on trials with the same difficulty level.

Visuospatial working memory task

Visuospatial working memory was assessed using the forward and backward condition of the computerized Grid Task (GT) developed by Nutley et al. (2009). A sequence of yellow dots was presented on a four by four grid. Children were required to repeat the sequence in the order of presentation (forward condition) or reversed order (backward condition) by clicking on the relevant locations in the grid. Trial difficulty was primarily determined by the length of the sequence, which increased with one dot every fifth trial. Trial difficulty was secondarily determined by the trajectory of the yellow dot within the grid (Nutley et al., 2009), which was more difficult in the second set of two trials

in sequences with a given length. The task was terminated after two consecutive incorrect responses on trials with the same difficulty level.

Stop Signal task

The Stop Signal Task (SST) was used to measure motor inhibition (Logan, 1994). The task involved Go trials and Stop trials. Go trials consisted of an airplane either pointing to the right or left side of the computer screen. Stop trials were identical to Go trials but with a stop signal superimposed on the airplane. Children were instructed to respond as quickly as possible to Go trials by pressing the corresponding button, and to inhibit the motor response when the stop signal was presented. The stop signal was presented with an initial delay of 175 ms after the onset of the stimulus and is lengthened or shortened by 50 ms on the next trial when the response was correct (successful motor response inhibition) or incorrect (failed motor response inhibition), respectively. This procedure titrates the latency of the stop signal in Stop trials to assess motor inhibition (measured by stop signal reaction time).

Wechsler Intelligence Scale for Children III

Full scale IQ was estimated by a two-subtest short form (Information and Block Design) of the Wechsler Intelligence Scale for Children III (WISC-III; Wechsler, 1991). This subset has good reliability and validity ($r_{xx} = .90$, $r = .85$; Sattler, 2001).

2.2.3 | Demographic variables

Additional information was collected by parent questionnaires to assess demographic information (sex, age, SES) and information on participation in sports. SES was defined as the average level of parental education ranging from 0 (no education) to 7 (post-doctoral education; Statistics Netherlands, 2006). Participation in sports was defined as parent-reported weekly participation in organized sports expressed in minutes, not including physical education, transport to school, and playing outside (Ooijendijk, Wendel-Vos, & De Vries, 2007).

2.3 | Study procedures

All participating children were tested within a period of 2 weeks. The 20-m SRT was conducted during a physical education lesson and was administered in groups of up to 15 children. The neurocognitive assessment was individually performed during the school day by trained examiners using standardized protocols, and tasks were administered in a fixed order. To prevent tiredness and distraction, the neurocognitive tasks were administered in two sessions performed on separate days, with a duration of 30–35 min per session. The study was approved by the ethical board of the Vrije Universiteit Amsterdam (Faculty of Behavioral and Movement Sciences), registered in the Netherlands Trial Register (number NTR5341) and was part of a cluster randomized controlled trial *Learning by Moving* (de Bruijn et al., 2019; Meijer et al. 2020; van der Fels et al., 2020).

2.4 | Data analysis

Preprocessing steps and statistical analysis were performed in IBM SPSS Statistics version 25.0 (SPSS IBM) and in R for Statistical Computing (R Foundation for Statistical Computing, Vienna, Austria). Outliers ($z \leq -3.29$ or ≥ 3.29) were winsorized, that is, replaced with a value one unit greater than the next non-outlier value (Field, 2013). To determine if data were normally distributed, histograms and values of skewness and kurtosis were visually inspected. Van der Waerden transformations were used to correct deviations from the normal distribution. Non-attendance of participating children during one of the two assessment days resulted in missing data. Prevalence of missing values ranged between 0% and 9% across all gathered data. Missing values at random were replaced by multiple imputation (Sterne et al., 2009). Individual scores on the ANT that were below change level were discarded from further analysis (upper endpoint of the 95% confidence interval around a random performance of 50% accuracy; $n = 13$). All neurocognitive measures were re-coded with higher scores indicating better performance.

To reduce the number of neurocognitive measures and to enhance their reliability, principal component analysis was performed on all measures derived from the neurocognitive tests (Table 2). Data were subjected to the principal component analysis with varimax rotation using the psych-package in R (Revelle, 2018). The scree plot was visually inspected and components were retained and subjected to further analysis. Factor loadings of $r > .30$ were considered relevant.

To relate cardiovascular fitness to executive functioning and to account for the clustered structure of our data (children clustered in school classes), mixed model analyses were conducted in IBM SPSS Statistics (SPSS IBM). Linear regression models were conducted in which the neurocognitive components (resulting from the principal component analysis) were used as dependent variables and cardiovascular fitness was included as predictor. A random intercept for school class was added to the model. Quadratic and cubic terms were added to the model to determine the best fit of the relationship between cardiovascular fitness and the neurocognitive components. Demographic variables (sex, grade [three or four], age and SES) were included in each model as covariates using a stepwise backward selection approach, providing a data-driven selection of relevant covariates for each dependent variable. To investigate whether significant relations between cardiovascular fitness and neurocognitive components were moderated by demographic characteristics or participation in organized sports, the interaction between cardiovascular fitness and the remaining significant covariates (i.e., sex, grade or SES) and sports participation were added to the model. Significant interaction effects were retained in the model. Executive functions and IQ are considerably overlapping constructs (Duncan, Schramm, Thompson, & Dumontheil, 2012). The same applies to BMI and fitness (Ruiz et al., 2006). Statistical models are not able to discriminate the individual contributions of separate variables (e.g., executive functions and IQ) to their shared variance that is related to a third variable (e.g. cardiovascular fitness; Miller & Chapman, 2001). Consequently, adding interrelated covariates creates the risk of

removing relevant variance from the relation between variables of interest, thereby underestimating their true relation. Hence, we chose not to add IQ and BMI as covariates. Effect sizes were calculated for all relationships and were interpreted using Cohen's guidelines, including definitions of small ($d = 0.2-0.5$), moderate ($d = 0.5-0.7$), and large effect sizes ($d > 0.7$; Cohen, 1988).

For each neurocognitive component showing a significant relation with cardiovascular fitness, we explored which specific neurocognitive function task variables contained in the component, contributed to the observed relation. Mixed model linear regression models were estimated in which these specific neurocognitive task measures (Table 2) were used as dependent variables and cardiovascular fitness was included as predictor. For these regression analyses, we used the same strategy as described for the regression models at component-level. Level of significance was set at 0.05 (two-sided).

3 | RESULTS

The raw scores for cardiovascular fitness and the neurocognitive function task variables are presented in Table 3.

3.1 | Principal component analysis

The principal component analysis extracted a total of six components from the neurocognitive data, which together explained 70% of the total variance (see Table 4). Based on the variables with the strongest contributions (i.e. factor loadings), the neurocognitive components were labeled as follows: (1) Information Processing and Control, (2) Attention Accuracy, (3) Visuospatial Working Memory (4) Interference Control (5) Verbal Working Memory, and (6) Attention Efficiency. See Table 4 for an overview of neurocognitive components, the factor loadings of neurocognitive variables, and the tasks used to measure these variables.

3.2 | Cardiovascular fitness and the neurocognitive components

Table 5 shows the results of the linear mixed model analysis, assessing the relation between cardiovascular fitness and the neurocognitive function components. The results revealed significant and positive relations between cardiovascular fitness and performance on the Information Processing and Control component ($B = 0.032$,

Measures		Mean (SD)	Range
Cardiovascular fitness	VO2max (ml kg ⁻¹ min ⁻¹)	48.37 (4.33)	36.47 to 61.86
Information processing	Information processing speed (MRT in ms)	648.81 (93.05)	446.73 to 960.02
Lapses of attention	Tau	130.10 (47.38)	4.00 to 286.00
Alerting attention	Speed of alerting attention (MRT in ms)	-36.70 (32.11)	-135.84 to 65.69
	Accuracy of alerting attention (% correct)	-0.18 (3.07)	-10.11 to 10.50
Spatial attention	Speed of spatial attention (MRT in ms)	-33.43 (31.51)	-130.46 to 69.70
	Accuracy of spatial attention (% correct)	0.70 (2.90)	-9.00 to 10.72
Interference control	Speed of interference control (MRT in ms)	131.13 (63.28)	-12.89 to 351.09
	Accuracy of interference control (% correct)	-6.18 (6.77)	-37.50 to 5.56
Verbal working memory	Verbal short-term memory (correct responses × span)	32.06 (12.61)	8 to 74
	Verbal working memory (correct responses × span)	14.35 (8.57)	1 to 42
Visuospatial working memory	Visuospatial short-term memory (correct responses × span)	59.81 (23.81)	0 to 137
	Visuospatial working memory (correct responses × span)	46.90 (22.70)	0 to 121
Motor inhibition	Motor inhibition efficiency (SSRT in ms)	248.38 (49.08)	14.96 to 413.83

TABLE 3 Results for cardiovascular fitness and the neurocognitive measures

Abbreviations MRT, mean reaction time; SSRT, stop signal reaction time.

TABLE 4 Results of principal component analysis on the neurocognitive measures

Neurocognitive measures	Information Processing and Control	Attention Accuracy	Visuospatial Working Memory	Interference Control	Verbal Working Memory	Attention Efficiency
Information processing	0.878					
Lapses of attention	0.842					
Speed of alerting attention						-0.788
Accuracy of alerting attention		0.870				
Speed of spatial attention						0.821
Accuracy of spatial attention		-0.849				
Speed of interference control				0.785		
Accuracy of interference control				0.847		
Verbal short-term memory					0.825	
Verbal working memory					0.804	
Visuospatial short-term memory			0.860			
Visuospatial working memory			0.787			
Motor inhibition	0.563					
Eigenvalue	1.936	1.449	1.476	1.446	1.383	1.346
Variance explained by component	0.149	0.115	0.114	0.111	0.106	0.104

Note: Please refer to Table 2 for a description of the measures; Factor loadings > 0.300 are displayed.

Abbreviation: MRT, mean reaction time.

TABLE 5 Results of linear mixed model analysis relating cardiovascular fitness to neurocognitive function components

Neurocognitive component	Covariates ^a	B	SE	95% CI	p-value	Cohen's D
Information Processing and Control	Age, Grade	0.032	0.008	0.0174 to 0.048	<.001	0.14
Attention Accuracy	—	0.004	0.008	-0.012 to 0.201	.645	0.02
Visuospatial Working Memory	Age, Grade, SES	0.027	0.008	0.011 to 0.044	.001	0.12
Interference Control	Age, Grade	-0.002	0.009	-0.019 to 0.015	.801	0.00
Verbal Working Memory	Age, Grade, SES	0.002	0.008	-0.014 to 0.018	.811	0.02
Attention Efficiency	SES, Sex	0.018	0.009	0.000 to 0.035	.039	0.08

Note: Please refer to Table 2 for a description of the measures.

Abbreviation: SES, socio-economic status.

^aCovariates significantly related to the neurocognitive function component.

$p > .001$), the Visuospatial Working Memory component ($B = 0.027$, $p = .001$), and on the Attention Efficiency component ($B = 0.018$, $p = .039$). Analysis of the polynomial trends indicated that all relationships, only the linear trends were significant. Cardiovascular fitness was not significantly related to Attention Accuracy, Interference Control, and Verbal Working Memory. None of the covariates that were significantly related to the neurocognitive function components (see Table 5) or sports participation significantly interacted with cardiovascular fitness.

3.3 | Cardiovascular fitness and specific neurocognitive measures

Table 6 shows the results of the additional mixed model linear regression analysis, assessing the relation between cardiovascular fitness and specific neurocognitive measures that build up the Information Processing and Control component, the Visuospatial Working Memory component and the Attention Efficiency component (i.e. the neurocognitive components with significant relations to cardiovascular fitness). Within the Information Processing and Control component, cardiovascular fitness was significantly related to information processing speed ($B = 0.904$, $p < .001$) and tau ($B = 0.467$, $p < .001$). These results indicate that higher cardiovascular fitness was associated with faster information processing and less lapses of attention. In addition, an association between higher cardiovascular fitness and faster motor response inhibition just escaped conventional levels of significance ($B = 0.751$, $p = .065$). Regarding the Visuospatial Working Memory component, regression analyses revealed significant positive associations between cardiovascular fitness and both visuospatial short-term memory ($B = 0.502$, $p = .008$) and visuospatial working memory ($B = 0.777$, $p < .001$). These associations indicate that higher cardiovascular fitness was associated with better visuospatial short-term memory and visuospatial working memory. Within the Attention Efficiency component, cardiovascular fitness was significantly related to the speed of alerting attention ($B = -0.625$, $p = .025$), which indicates that higher cardiovascular fitness was associated with slower speed

of alerting attention. Cardiovascular fitness was not significantly related to speed of spatial attention. Analysis of the polynomial trends indicated that for all relationships only the linear trends were significant. None of the covariates that were significantly related to the executive function measures (see Table 6) or sports participation significantly interacted with cardiovascular fitness.

4 | DISCUSSION

The present study investigated the relationship between cardiovascular fitness and executive functioning in primary school-aged children. We extended the previous work by investigating the relationship between cardiovascular fitness and executive functioning in a large representative sample of healthy school-aged children, using a set of executive function and lower level neurocognitive function measures. The present study suggests that the relationship between cardiovascular fitness and executive functions applies to a set of specific executive functions and lower level neurocognitive functions, but not to all. Results showed that children with higher cardiovascular fitness performed better on the neurocognitive function components Information Processing and Control, Visuospatial Working Memory, and Attention Efficiency. We also explored which specific measures contained in these three components contributed to the observed relationships. Almost all measures contained in the components were found to contribute to the observed relationship, namely information processing speed, lapses of attention, visuospatial short-term memory, visuospatial working memory, and speed of alerting attention. Motor inhibition and speed of spatial attention did not contribute to the relationships. Despite the modest effect sizes ($d = 0.8-0.36$), all observed relationships translate into substantial impact at the level of the population. No meaningful relationships were found between cardiovascular fitness and the neurocognitive function components Interference Control, Verbal Working Memory, and Attention Accuracy.

Our findings suggest that specific neurocognitive functions are more sensitive to the effects of cardiovascular fitness than others. One possible explanation for these findings is that cardiovascular

TABLE 6 Results of linear mixed model analysis relating cardiovascular fitness to the neurocognitive measures contained in the neurocognitive function components Information Processing and Control, Visuospatial working memory and Attention Efficiency

Neurocognitive components and measures	Covariates ^a	B	SE	95% CI	p-value	Cohen's D
Information Processing and Control						
Information processing speed	Age, Grade, Sex	3.141	0.764	1.641 to 4.641	<.001	0.14
Tau	Grade	1.522	0.376	0.784 to 2.259	<.001	0.36
Motor inhibition efficiency	Grade, Sex	0.751	0.407	-0.047 to 0.493	.065	0.17
Visuospatial Working Memory						
Visuospatial short-term memory	Grade, SES	0.502	0.190	0.130 to 0.875	.008	0.12
Visuospatial working memory	Age, Grade, SES	0.777	0.183	0.417 to 1.137	<.001	0.18
Attention Efficiency						
Speed of alerting attention	SES, Sex	-0.625	0.278	-1.171 to -0.080	.025	0.15
Speed of spatial attention	—	0.380	0.259	-0.129 to 0.888	.143	0.09

Note: Please refer to Table 2 for a description of the measures.

Abbreviation: SES, socioeconomic status.

^aCovariates significantly related to the neurocognitive function component.

fitness exerts its effects only on those brain structures that are involved in these specific executive functions. Neuroelectric research confirms the acute and beneficial effects of physical activity on attention resources which seem to primarily stem from frontal lobe structures such as the anterior cingulate cortex (Hillman, Kamijo, & Scudder, 2011). The effects of prolonged physical activity and higher cardiovascular fitness might be a result of accumulation of these acute effects. Interestingly, neuroimaging studies suggest that the observed relationship between physical fitness and lapses of attention and inhibition is mediated by enhanced white matter integrity of structures in the frontal lobes (Bellgrove, Hester, & Garavan, 2004; Botvinick, Cohen, & Carter, 2004; Lin et al., 2014; Voss et al., 2013). Besides, visual spatial working memory performance is also associated with activation in frontal lobes (Klingberg, Forssberg, & Westerberg, 2002; van Ewijk et al., 2015). This strengthens the idea that physical activity might improve executive functioning, attentional resources, and information processing through enhancement of white matter integrity of the frontal lobes. Unfortunately, only a very limited number of studies have investigated these neuronal underpinnings of the relationship between cardiovascular fitness and neurocognitive functioning in children (Schaeffer et al., 2014).

A recent meta-analysis and systematic review indicated that prolonged physical activity in children have beneficial effects on working memory, interference control, and attention (Donnelly et al., 2016; de Greeff et al., 2018). Interestingly, in the current study we did not find a meaningful relationship between cardiovascular fitness and the neurocognitive function components like Interference Control, Verbal Working Memory, and Attention Accuracy. When looking more closely into earlier studies, we noticed that these studies used traditional executive function tasks (e.g. paper and pencil tasks) or used measures assessing a multitude of cognitive functions including aspects of executive functioning. The use of these entangled measures of neurocognitive functioning might be a possible explanation for the contradictory results. Our

results concerning working memory and interference control confirm this idea. With regard to working memory, most previous studies did not differentiate between verbal and visual spatial memory, but rather used a single task to assess working memory containing a combination of working memory aspects, such as the n-back task (Drollette et al., 2016; Scudder et al., 2014). We only found a relationship between cardiovascular fitness and Visual Spatial Working Memory, but not with Verbal Working Memory. Previous findings of positive associations between cardiovascular fitness and measures of working memory might therefore have been carried by the relationship between cardiovascular fitness and visuospatial working memory.

One possible explanation for the discrepant findings concerning interference control is that previous studies did not take speed of information processing into account (Chaddock et al., 2012; Hillman et al., 2009; Kao et al., 2017; Pontifex et al., 2011; Scudder et al., 2014; Wu et al., 2011). Such an explanation is confirmed by our data. However, we found no significant relationship between cardiovascular fitness and interference control, exploratory analyses using mean reaction time measured on incongruent trials of the ANT as a measure of interference control, showed a significant relationship between cardiovascular fitness and interference control ($p < .001$). These findings indicate that, when isolating information processing efficiency from interference control accuracy, cardiovascular fitness is related to information processing efficiency. Our data also showed that the relationship between cardiovascular fitness and interference control was not significant when the analysis was adjusted for information processing efficiency. Besides, the underlying role of information processing efficiency could also be an explanation for the failure to find a meaningful relationship between cardiovascular fitness and attention accuracy. Most attention tasks that were used in previous studies were tasks measuring reaction times, strongly relying on information processing efficiency

(Syväoja et al., 2014). Furthermore, the negative relationship between cardiovascular fitness and speed of alerting attention in our study may indicate that children with higher cardiovascular fitness are less dependent on alerting attention or have less room for improvement due to a faster information processing efficiency. However, in combination with the positive relationship between cardiovascular fitness and overarching neurocognitive component Attention Efficiency it may also indicate that attention in general is more efficient when the contribution of alerting attention is smaller. Taken together, our findings indicate that the previously reported relationship between cardiovascular fitness and both interference control and attention might in fact be carried by information processing efficiency. These findings emphasize the importance of using measures of executive functioning that do control for other aspects of neurocognitive functioning involved in task performance.

Our study has some important strengths such as the large sample size and the well-defined set of neurocognitive function measures. Nevertheless, this study also has some limitations. First, the study used cross-sectional data, which makes it impossible to study the causal relationship between cardiovascular fitness and executive functioning. Nevertheless, there is widespread evidence supporting the idea that cardiovascular fitness causally impacts on brain structure and neurocognitive functioning (Donnelly et al., 2016). Second, to assess cardiovascular fitness we performed a submaximal physical fitness test (20 m Shuttle Run Test), while a maximal fitness test is considered as the gold standard to assess cardiovascular fitness (American College of Sports Medicine, 2013). Due to the practical considerations relating to group-wise assessments, we have chosen a submaximal physical fitness over a maximal test. Third, we assessed the physical activity level of children by a parent-reported questionnaire (Ooijendijk et al., 2007). Future research should include objective measures of physical activity for example, as recorded with accelerometers. Furthermore, cardiovascular fitness is a complex concept and can be influenced by many factors such as muscular strength and motor coordination, which were not assessed in the present study (Armstrong, 2017). Also, genetic make-up is related to both the development of physical fitness and neurocognitive performance (Malina et al., 2004). Randomized, controlled trials are necessary to account for potential bias and to establish the hypothesized causal relationship between cardiovascular fitness and executive function in children.

Findings of the present study have important implications. Despite the modest effect sizes, the impact of our findings for information processing measures, motor inhibition, and visuospatial working memory, translate into substantial effects at the population level. The results confirm the importance of cardiovascular fitness in children and indicate that increasing children's cardiovascular fitness might be a promising method to benefit information processing measures, motor inhibition, and visuospatial working memory. These functions, in turn, are crucial for behavioral functioning, academic achievement, health, wealth, and quality of life throughout (Bull, Espy, & Wiebe, 2008; Diamond &

Lee, 2011; Moffitt et al., 2011). Furthermore, the positive linear relationship between cardiovascular fitness and specific neurocognitive functions shown in our study, suggest that prolonged physical activity leads to enhanced executive functioning. This is in line with a growing body of studies that indicate that moderate to vigorous physical activity (50%–85% of the maximum heart rate) has larger beneficial effects on executive functioning compared to light physical activity (de Greeff et al., 2018; McMorris & Hale, 2012). In light of the current decline in cardiovascular fitness among children (Tomkinson, Lang, & Tremblay, 2019), the observed relationship between cardiovascular fitness and executive functioning underlines the need of randomized controlled trials investigating the hypothesized causal effects of physical activity on executive functioning. Furthermore, future studies should also focus on manipulating intensity of physical activity (i.e. light, moderate, and vigorous) in order to increase the understanding of the optimal intensity level of physical activity for enhancing neurocognitive functioning in children. Brain imaging might complement such studies, to elucidate the operating brain mechanisms. For example, diffusion tensor imaging might be used to study changes in white matter integrity resulting from physical activity.

The present study in school-aged children demonstrated a significant relationship between cardiovascular fitness and specific executive functions and lower level neurocognitive functions, including information processing speed, lapses of attention, visuospatial working memory, and speed of alerting attention. However, cardiovascular fitness showed no significant relationship with other executive functions or lower level cognitive functions. The current findings support the idea that regular physical activity during school-ages may facilitate specific aspects of executive functioning. These findings highlight the importance of cardiovascular fitness for the overall health of school-aged children.

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CONFLICT OF INTEREST

All authors have no conflicts of interest to disclose relevant to this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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