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The Indirect Role of Executive Functions on the Relationship between Cardiorespiratory Fitness and School Grades

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[1]Faculty of Psychology, University of Geneva, Geneva, SWITZERLAND; [2]Distance Learning University, Brig, SWITZERLAND; [3]Campus Biotech, 9 Chemis des Mines, Geneva, SWITZERLAND; and [4]Department of Psychology and Department of Physical Therapy, Movement, and Rehabilitation Sciences, Northeastern University, Boston MA

ABSTRACT

YANGÜEZ, M., B. BEDIOU, C. H. HILLMAN, D. BAVELIER, and J. CHANAL. The Indirect Role of Executive Functions on the Relationship between Cardiorespiratory Fitness and School Grades. *Med. Sci. Sports Exerc.*, Vol. 53, No. 8, pp. 1656–1665, 2021. **Purpose:** The aim of this study was to investigate the indirect effects of cardiorespiratory fitness on scholastic performance through executive functions. More precisely, we examined the contribution of the different domains of executive functions, and whether this relationship was specific to certain school topics. **Methods:** Children 8–12 yr old completed nine cognitive tests and the multistage fitness test. Structural equation modeling techniques were used to analyze the role of different domains of executive functions (inhibition, working memory, cognitive flexibility, and a common factor to all tasks) in the relationship between cardiorespiratory fitness and school grades in three domains: (i) mathematics; (ii) grammar, spelling, and vocabulary; and (iii) text comprehension and expression. Covariate analyses included age and socioeconomic status. **Results:** The results of this study showed that an indirect effect of the various domains of executive functions explained, in part, the relationship between cardiorespiratory fitness and (i) mathematics ($\beta = 0.12$, SE = 0.03, $P < 0.001$), and between cardiorespiratory fitness and (ii) grammar, spelling, and vocabulary ($\beta = 0.12$, SE = 0.03, $P < 0.001$). No relationship between cardiorespiratory fitness and (iii) text comprehension and expression was observed. Although executive functions correlated with school grades, cognitive flexibility drove the indirect effect when all executive function domains were simultaneously taken into account. **Conclusions:** These results show the role that executive functions play in understanding the relationship between cardiorespiratory fitness and scholastic performance. Importantly, not all executive function domains contributed equally because cognitive flexibility played a leading role in this wide age range. Furthermore, the relationship between cardiorespiratory fitness and scholastic performance was strongest for mathematics and for low-level language topics but nonsignificant for higher-level language topics, providing a more modulated view of the effect of cardiorespiratory fitness on language. **Key Words:** CARDIORESPIRATORY FITNESS, EXECUTIVE FUNCTIONS, SCHOLASTIC PERFORMANCE, MULTIPLE MEDIATION, STRUCTURAL EQUATION MODELING, CHILDREN

Global trends in physical activity (PA) indicate that many children and adolescents do not meet current PA guidelines (1). Primary school provides an opportunity for all children to engage in PA through physical education lessons. However, time spent in moderate to vigorous PA (MVPA) in physical education lessons not only does not meet recommendations by policymakers but also decreases from 8 to 12 yr old (2). This is particularly problematic because PA is associated with several physical and psychological benefits across the life span (3). Children's PA levels are moderately associated with cardiorespiratory fitness (4), a marker of cardiovascular health that has been related to scholastic performance, as exemplified by a recent meta-analysis (5). The pooled effect sizes reported indicate a small to moderate effect of cardiorespiratory fitness on specific academic domains such as mathematics (0.23; 95% confidence interval [CI] = 0.19–0.36) and language/reading (0.23; 95% CI = 0.12–0.34), but also with overall scholastic performance as measured by composite scores (0.28; 95% CI = 0.12–0.45). Interestingly, age moderated the association between cardiorespiratory fitness and scholastic performance with younger children (i.e., 6–9 yr old) showing stronger effects than their older counterparts (i.e., 10–12 yr old).

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The present study extends this area of research by investigating whether executive functions, a key aspect of cognition for school success, may act as a mediating mechanism by which cardiorespiratory fitness affects scholastic performance in a sample of 8- to 12-yr-old children.

Executive functions encompass different cognitive skills, with three subprocesses—inhibition, working memory, and cognitive flexibility—considered to be central to executive functions (6) and fundamental for success in school (7,8). Inhibition enables the suppression of reactions to salient or distracting stimuli; working memory involves not only holding information in mind but also performing mental manipulations on it; and cognitive flexibility enables the switching between different rules, goals, or task demands at will (for a review, see Diamond [6]).

The relationship between cardiorespiratory fitness and children's executive functioning has been shown in cross-sectional studies (9,10) as well as in randomized controlled trials (11,12), with increased cardiorespiratory fitness being associated with positive effects on multiple cognitive outcomes, especially executive functions. Accordingly, a recent meta-analysis documents small to moderate effects of PA training programs aimed at increasing cardiorespiratory fitness on executive functions (0.24; 95% CI = 0.09–0.39). Regarding the effect of PA on specific domains of executive functions, the authors reported positive effects on working memory (0.36; 95% CI = 0.10–0.62) and cognitive flexibility (0.18; 95% CI = 0.01–0.35) with no significant effects on inhibition (13). In parallel, there is a growing literature linking executive functions to scholastic achievement, showing that enhanced executive functioning is related, in particular, with mathematics and language performance (14). However, the exact contribution of the different executive function processes to subdomains of scholastic performance such as mathematics or language remains unclear given the mixed results reported in the literature (7,8,14).

Few studies have asked whether executive functions mediate the relationship between PA outcome measures (e.g., motor ability, weekly hours of MVPA, aerobic fitness, etc.) and scholastic performance. Aadland et al. (15) conducted a 7-month longitudinal study and concluded that executive functions (conceptualized as a single latent construct) do not mediate the relationship between several indices related to PA (e.g., aerobic fitness, MVPA, etc.) and performance in numeracy, reading, and English tests. Conversely, Schmidt et al. (16) and Van der Niet et al. (17) showed that a latent construct estimating executive functions mediated the relationship between different indices related to PA (motor ability and physical fitness, respectively) and overall scholastic performance. Schmidt et al. (16) addressed this question using a longitudinal design, whereas Van der Niet et al. (17) used a cross-sectional design. Heterogeneity in the methodology of these studies (e.g., design, PA measures, or executive function evaluation and conceptualization) limits possible conclusions regarding this question. In particular, these studies treated executive functions as a unitary construct, rather than a combination of at least three distinct cognitive processes (18), that may contribute differently to explain scholastic performance, as it has been shown previously (7,8). The conception of executive functions as a unitary construct by these studies was determined by a limited battery of tasks used, which did not enable the estimation of latent constructs for the three main domains of executive functions. Schmidt et al. (16) used a nonspatial n-back task to measure the updating component of working memory and two versions of a flanker task to measure inhibition and cognitive flexibility. The tasks used by Van der Niet et al. (17) did not tap inhibition or working memory, only focusing on cognitive flexibility and planning. Therefore, the representativeness of the executive functions construct included in the mediation models of these studies remains unclear. A multitask approach to measuring each distinct component of executive functions (i.e., inhibition, working memory, and cognitive flexibility) addresses the issue of task impurity and unreliability through the use of latent variable procedures but also enables a more representative model of executive functions made of distinguished and interrelated latent constructs (18). In accordance with the best practices in the field of executive functions, the present study takes a multitask approach to evaluate each component of executive functions, enabling the ability to disentangle the executive functions mechanisms underlying the relationship between cardiorespiratory fitness and scholastic performance.

Our study aimed to confirm existing results in the literature and test two new hypotheses. Relative to the confirmation of existing results, it was hypothesized that

(a) higher cardiorespiratory fitness would be associated with better scholastic performance in three school subdomains: (i) mathematics; (ii) grammar, spelling, and vocabulary; and (iii) text comprehension and expression;
(b) higher cardiorespiratory fitness would be associated with enhanced ability in different domains of executive functions;
(c) upon confirmation of these results, this study tested two novel main hypotheses: the relationship between cardiorespiratory fitness and scholastic performance would be explained by an indirect effect through executive functions;
(d) executive function components would differentially contributed to this relationship.

In sum, the main objective of the present study was to investigate the extent to which the different domains of executive functions explained the relationship between cardiorespiratory fitness and scholastic performance in a sample of 8–12 yr old. This work extends previous research (15–17) by taking a more comprehensive approach to executive functions via latent variable procedures.

METHODS

Procedure

Children were recruited from eight primary schools in Geneva (Switzerland) via flyers distributed by the schoolteachers. In agreement with the Ethics Committee of the University of Geneva, which approved this research, written informed consent was obtained before parents completed an online survey to provide information about their children's physical and mental health. This survey was used to screen children for the following exclusion criteria: diagnosis of a learning or development disorder (e.g., dyslexia, attention deficit hyperactivity disorder, autism, etc.) or a medical condition for which exercise is contraindicated. Data collection occurred over two different school years and was conducted by trained research assistants in the school facilities. Fitness (session 1) and cognitive assessment (sessions 2 and 3) occurred within a 4-wk period, distributed between January and early June of each school year. The fitness assessment was conducted during the physical education lesson. First, anthropometric measurements were collected via height and weight assessments with children barefooted and lightly dressed. Next, the multistage fitness test (19) was administered. In sessions 2 and 3, the cognitive assessment occurred in a quiet room in the school, where testing occurred in groups of two to four children. Finally, at the end of the school year, teachers submitted the students' grades over three trimesters. Note that grades on the third trimester correspond to the teachers' assessments in late June.

Participants

A total of 193 children participated in the study and completed nine executive function tasks, from which 178 children completed the multistage fitness test. Furthermore, we obtained legal consent to receive the grades from 169 children; however, schoolteachers submitted the grades over three trimesters from only 150 children. At the end of the study, 11 children were excluded from the final sample due to diagnosis of a learning disability reported by their parents. Therefore, the final sample included 182 children (92 female), although there is missing data from the multistage fitness test (n = 169) and school grades (n = 139). Their mean age was 10.53 ± 1.17 yr. Children's chronological age ranged from 8.0 to 12.75 yr (see Table 1).

Measures

Cardiorespiratory fitness assessment. The multistage fitness test (19) requires continuous running between two lines 20 m apart. At the beginning, the speed is relatively slow (8.5 km·h^{-1}), with progressive increases every minute (level) as indicated by the auditory tones (+0.5 km·h^{-1}). The last achieved stage number (or level), the equivalent maximal speed or the number of laps, are taken as the score on this test. The primary measure of cardiorespiratory fitness is maximal oxygen consumption ($\dot{V}O_{2max}$). Three equations from the existing literature were used to estimate $\dot{V}O_{2max}$ from the multistage fitness test results. These equations differ slightly, including test performance (maximal speed vs number of laps), participant demographics (age and sex), or anthropometric measurement (height and weight vs body mass index).

The equation of Leger et al. (19) is as follows:

$$\dot{V}O_{2max} = 31.025 + (3.238 \times \text{speed}) - (3.248 \times \text{age}) + (0.1536 \times \text{speed} \times \text{age}),$$

where speed corresponds to the maximal speed in kilometers per hour attained on the multistage fitness test, and age is in years. The equation of Barnett et al. (20) is as follows:

$$\dot{V}O_{2max} = 25.8 - (6.6 \times \text{gender}) - (0.2 \times \text{mass in kg}) + (3.2 \times \text{speed}),$$

where gender = 0 (boy) or 1 (girl). The equation of Matsuzaka et al. (21) is as follows:

$$\dot{V}O_{2max} = 61.1 - (2.2 \times \text{gender}) - (0.462 \times \text{age}) - (0.862 \times \text{body mass index}) + (0.192 \times \text{laps}),$$

where laps correspond to the number of laps in the multistage fitness test.

Cognitive assessment. To estimate inhibition, working memory, and cognitive flexibility, we used nine tasks (see Table 2). All tasks were computer based, except for the Trail Making Test, which was a paper–pencil task (see Appendix 1, Supplemental Digital Content 1, Executive functions measures, http://links.lww.com/MSS/C268).

Task performance indicators. For inhibition and cognitive flexibility tasks, children were asked to answer as quickly and as accurately as possible.

Inhibition tasks. Flanker (11) and Simon (22) tasks have multiple conditions that modulate inhibition requirements, but incongruent trials in these two tasks require the greatest inhibitory control demands because of perceptual interference and/or response conflict. Therefore, the inverse efficiency score [response time/(1 − error rate)] (29) on incongruent trials was used as performance indicator. For the go/no-go task (10), we calculated d' based on performance in the second block of the task, which requires an upregulation of response conflict (30).

Working memory tasks. For the letter memory task (23) and spatial n-back task (24), the performance measure was the percentage of correct responses (only 2-back trials in the latter). In the digit span task (25), the longest sequence that was remembered correctly (i.e., the span length) was used as a measure of working memory span.

Cognitive flexibility tasks. Switch trials are the most diagnostic of cognitive flexibility, as they require participants to switch task goals. Therefore, for the color–shape (26) and gender–smile (27) switching tasks, the inverse efficiency

TABLE 1. Participants characteristics.

	All Children			Girls			Boys		
	N	Mean	SD	*N*	Mean	SD	*N*	Mean	SD
Age	182	10.53	1.17	92	10.53	1.2	90	10.52	1.14
Height (cm)	180	144.69	8.86	90	145.43	8.70	90	143.95	9.01
Weight (kg)	179	37.98	9.56	89	38.66	9.68	90	37.3	9.44
BMI	179	17.84	3.43	89	17.87	3.7	90	17.81	3.17
Multistage fitness test (number of laps)	169	39.92	19.62	81	32.66	15.12	88	46.6	20.94
SES	159	10.21	1.64	81	10.3	1.53	78	10.11	1.75

Age corresponds to chronological age. BMI, body mass index; SES, socioeconomic status, scale from 4 to 13.

TABLE 2. Cognitive tasks, acronyms, and performance outcome indicators.

EF Construct	Task	Acronym	Indicator
Inhibition	Go/no-go task (10)	GNG	*d'* second block of the task
	Flanker task (11)	FT	Incongruent trials efficiency score
	Simon task (22)	ST	Incongruent trials efficiency score
Working memory	Letter memory task (23)	LMT	% correct responses
	Spatial n-back task (24)	SNB	% correct responses 2-back trials
	Backward digit span task (25)	BDST	Digit span length
Cognitive flexibility	Color–shape switch task (26)	CSST	Switch trials efficiency score
	Gender–smile switch task (27)	GSST	Switch trials efficiency score
	Trail Making Test (28)	TMT	TMT-B RT in seconds

score for switch trials was used as indicator of performance. For the Trail Making Test (28), the performance indicator was the number of seconds needed to complete the trails B test, which requires continuously switching between two different task sets.

School grades. Students' grades over three trimesters on three school subjects were collected: (i) mathematics and two domains of language; (ii) grammar, spelling, and vocabulary; and (iii) text comprehension and expression.

Family socioeconomic status (SES). SES was assessed through the Family Affluence Scale (31), which contains the following items: (a) Does your family own a vehicle (car, van, etc.)? (b) Does your child have his own room? (c) In the last 12 months, how many times did the family go on holidays? (d) How many computers does your family have? Among the 182 children included in the final sample, parents provided SES from 159 children.

Statistical Procedures

Raw data cleaning and preparation was conducted with R (version 3.6.1). Then data analyses were conducted using Mplus version 8.3 (32). Structural equation models were first conducted to extract factor scores of different assessments made (cardiorespiratory fitness, executive functions, and grades). Multiple mediation models were then conducted with this new data set to test our main objective. Several indices were used to evaluate the fitting of each model to the data: comparative fit index (CFI), Tucker–Lewis index (TLI), root-mean-square error of approximation (RMSEA), and standardized root mean residual (SRMR). The criteria for excellent model fit based on these indices are greater than 0.95 for CFI and TLI and less than 0.05 for RMSEA and SRMR; however, a CFI/TLI > 0.90 and an RMSEA or SRMR <0.08, respectively, are considered acceptable (33).

Raw data cleaning. For computer tasks in which response time (RT) was recorded (FT, ST, GNG, CSST, GSST, and SNB; acronyms described in Table 2), we computed participants' mean RT and SD per task condition based on correct trials. Trials with RT below 200 ms were considered anticipatory responses and removed. For each participant, trials with a RT beyond ±2.5 SD from within-subject mean were removed.

For all tasks, we calculated nine performance indicators for each participant (one per task) and transformed each of them into *z*-scores. Then univariate analyses were conducted on the nine indicators to remove outliers. As a result, if a value was greater than 3 SD from the sample mean, that individual subject task data were excluded from the analyses. This affected less than 1.5% of observations.

Data analyses. *Cardiorespiratory fitness latent construct.* Confirmatory factor analysis (CFA) was used to compute a cardiorespiratory fitness latent variable based on the outcome of the three equations (19–21) that were used to estimate $\dot{V}O_{2max}$. These equations differ in the parameters used to estimate cardiorespiratory fitness. A latent variable approach was used to (a) overcome these differences and (b) reduce the measurement error associated with each equation. Therefore, after conducting CFA, we extracted factor scores of cardiorespiratory fitness from this model for each child for posterior analyses.

Latent executive function constructs. CFA was conducted to test the fitting of a four-factor model of executive functions (see Fig. 1). This model includes a global factor that captures what is common between all the tasks and three subfactors referred as inhibition, working memory, and cognitive flexibility. We extracted the factor scores of the four constructs of the model (from each participant) for the subsequent analyses.

Grades. Latent growth curve models based on the grades over three trimesters obtained in each school subject were built to estimate students' grades level (intercept) at the end of the year (on the third trimester, and student's growth rate (slope) across the school year for each school subject. This approach has the advantage over averaging the grades from the three trimesters because it estimates the latent score of the intercept at time 3 for each student, considering not only the two previous grades (T1 and T2) but also the trajectory of grades across the academic school year for the total sample (34). Based on these models, individuals' intercept factor scores were extracted representing children's level at the end of the school year on these three school topics.

Multiple mediation models. Next, structural equation modeling was used to test our main hypotheses (see Fig. 2). In this model, the total effect of cardiorespiratory fitness on grades could be decomposed in direct (path a) and indirect effects. Multiple indirect effects are simultaneously tested: a simple indirect effect for each specific component, inhibition (path cg), working memory (path dh), and cognitive flexibility (path ei), and for the global component (path bf). A global indirect effect is also obtained through the analyses to determine whether total effect is more due to direct or to indirect effects. Note that this study does not allow for the control of school

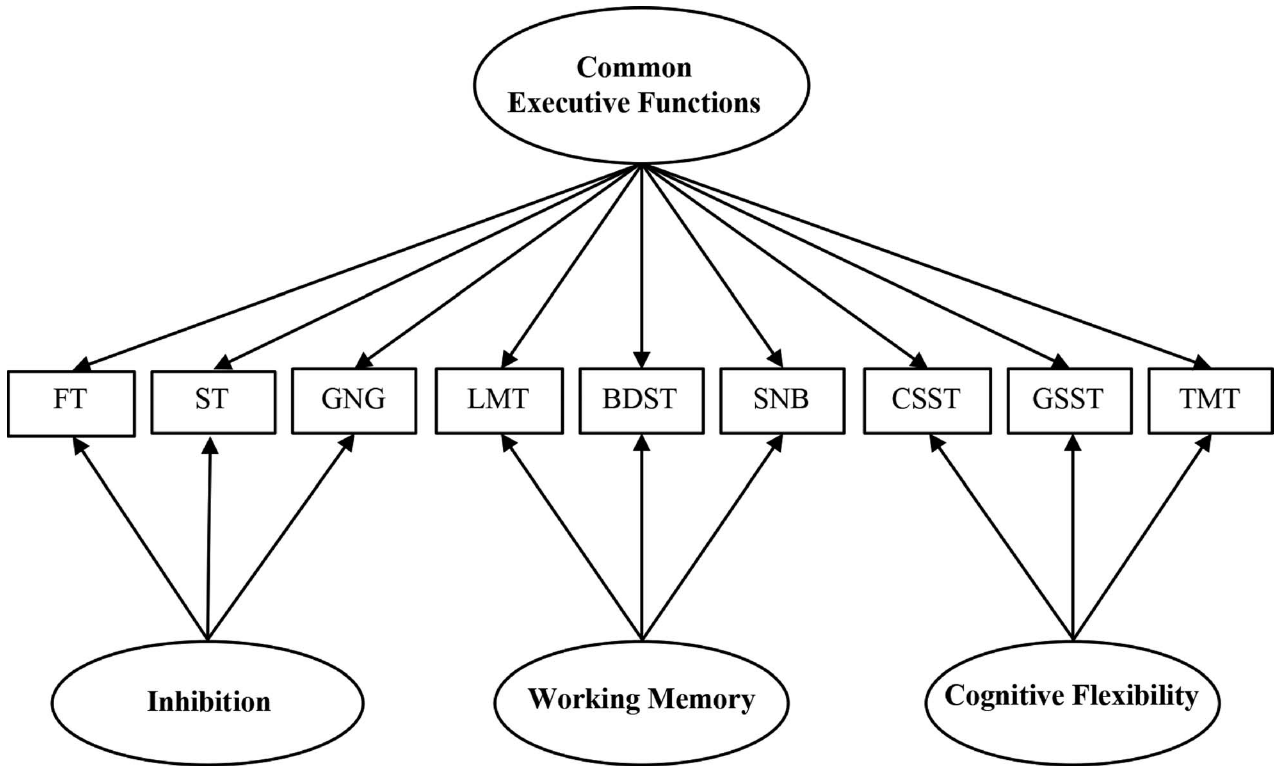

FIGURE 1—Executive function model: all nine executive function tasks load into a factor named common executive function, which represents what is common between the nine executive function tasks and, hence, what is common between the three latent factors. Then inhibition, cognitive flexibility, and working memory tasks load into its corresponding factor, representing what is specific to each executive function construct. Tasks' acronyms described in Table 1.

effects as the distribution of children across the different schools was too heterogeneous.

RESULTS

Latent Variable Models

Cardiorespiratory fitness latent construct. The fit index of the model was perfect.

Latent executive function construct. The model tested (see Fig. 1), which included four factors, reached an excellent fit (CFI = 0.980, TLI = 0.953, RMSEA = 0.041, SRMR = 0.031).

Grades. Latent growth curve models were built (a) with intercept only and (b) with intercept and linear slope. The best model for mathematics (CFI = 0.959, TLI = 0.878, RMSEA = 0.204, SRMR = 0.028) and grammar, spelling, and vocabulary (CFI = 1.000, TLI = 1.007, RMSEA = 0.000, SRMR = 0.011) was the intercept and slope model, whereas for text comprehension and expression, the best model was the intercept only model (CFI = 0.992, TLI = 0.994, RMSEA = 0.044, SRMR = 0.148) (see Table S1, Supplemental Digital Content 2, Latent growth curve models for school grades over three trimesters, http://links.lww.com/MSS/C269).

Multiple Mediation Model of Cardiorespiratory Fitness, Executive Functions, and Grades

Correlations between all the variables measured can be found in Table 3. The three subprocesses of executive functions remained strongly correlated, inhibition with cognitive flexibility, $r(180) = 0.70$, $P < 0.001$, and working memory, $r(180) = 0.76$, $P < 0.001$, and cognitive flexibility with working memory, $r(180) = 0.78$, $P < 0.001$. Furthermore, mathematics correlated with working memory, $r(137) = 0.21$, $P = 0.015$, and cognitive flexibility, $r(137) = 0.30$, $P < 0.001$; grammar, spelling, and vocabulary correlated with inhibition, $r(137) = 0.17$, $P = 0.042$, working memory, $r(137) = 0.23$, $P = 0.006$, and cognitive flexibility, $r(137) = 0.32$, $P < 0.001$; and text comprehension and expression correlated with inhibition, $r(137) = 0.27$, $P = 0.001$, working memory, $r(137) = 0.31$, $P < 0.001$, and cognitive flexibility, $r(137) = 0.36$, $P < 0.001$. When considering fitness, cardiorespiratory fitness was related with mathematics, $r(130) = 0.23$, $P = 0.007$, and grammar, spelling, and vocabulary, $r(130) = 0.19$, $P = 0.028$, as well as with working memory, $r(167) = 0.25$, $P = 0.001$, and cognitive flexibility, $r(167) = 0.27$, $P < 0.001$. SES was associated with cardiorespiratory fitness, $r(147) = 0.17$, $P = 0.035$, and cognitive flexibility, $r(157) = 0.16$, $P = 0.041$.

Note that the multiple mediation models presented below were also run controlling for the effect of age and SES. Because no differences in the results were found when controlling for SES (n = 159), we only present models controlling for age because the sample size was notably reduced when also controlling for SES due to missing data (see Table S2, Supplemental Digital Content 3, Bootstrap results for specific and global indirect effects, and total effects in the multiple mediation analyses, http://links.lww.com/MSS/C270). Furthermore,

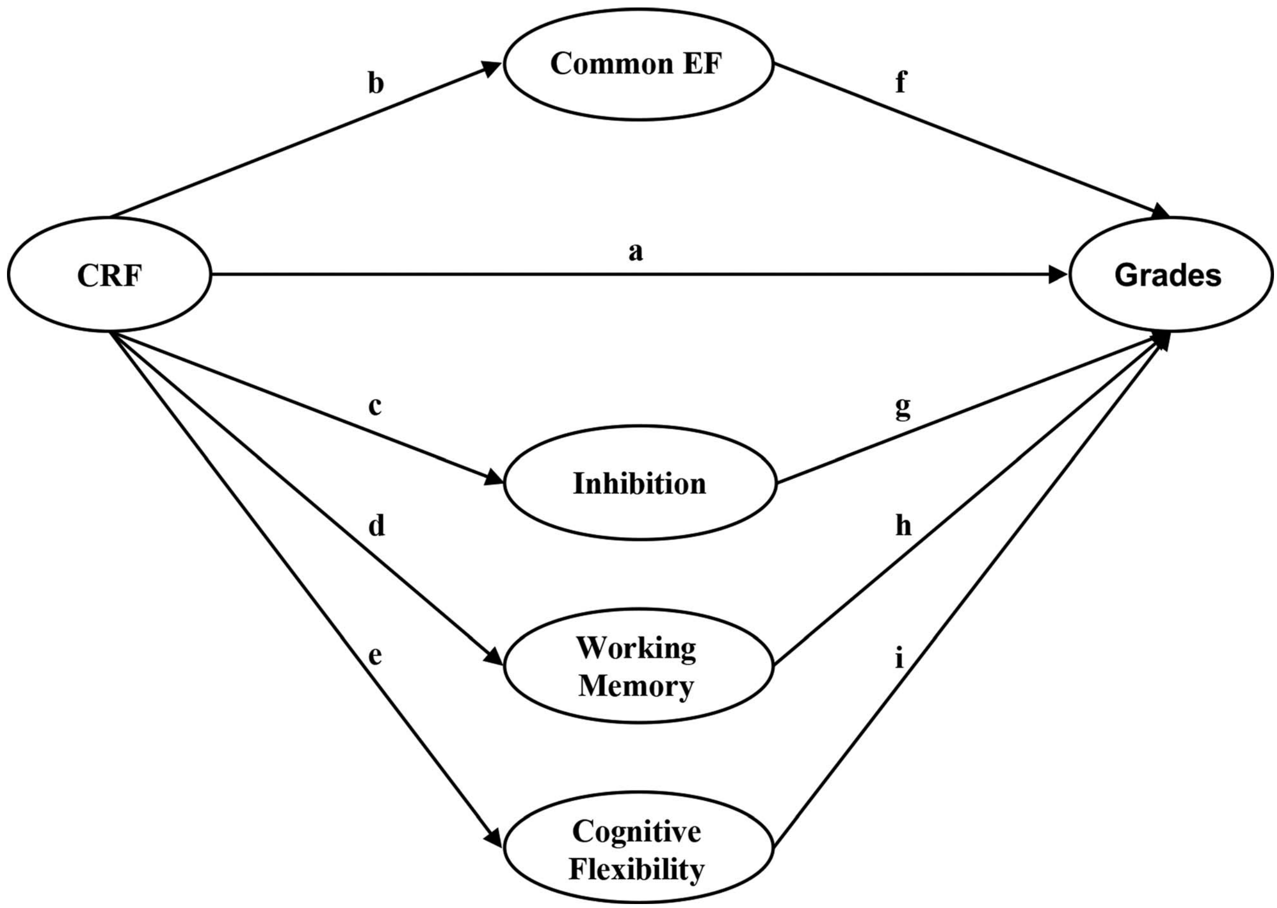

FIGURE 2—Multiple mediation model. CRF= cardio respiratory fitness; EF = executive functions. Direct effect = a; specific indirect effect common EF = bf; specific indirect effect inhibition = cg; specific indirect effect working memory = dh; specific indirect effect cognitive flexibility = ei; global indirect effect = bf + cg + dh + ei; total effect = direct effect + global indirect effect.

our main findings remain unchanged when only those participants without any missing data are include (n = 132). Our results remain also unchanged when conducting the same analysis without a common construct (see Table S3, Appendix 2, Supplemental Digital Content 4, Mediation analyses three-factor model, http://links.lww.com/MSS/C271); however, the bifactor model was preferred because it has a better fitting (see Table S4, Appendix 2, Supplemental Digital Content 4, Fit indices of executive functions models, http://links.lww.com/MSS/C271).

Multiple mediation model for mathematics. The direct path from cardiorespiratory fitness to mathematics grades, without executive functions as a mediator in the model, was significant (β = 0.26, SE = 0.05, P = 0.002). This path coefficient decreased to a nonsignificant level when executive functions were included in the model (β = 0.16, SE = 0.08, P = 0.052). The multiple mediation test revealed a total effect on mathematics (β = 0.28, SE = 0.08, P = 0.001, R^2 = 0.30), explained by a global indirect effect through the different executive function components (β = 0.12, SE = 0.03, P < 0.001). This global indirect effect was mostly driven by a specific indirect path through cognitive flexibility (path ei: β = 0.11, SE = 0.04, P = 0.007). More specifically, cardiorespiratory fitness predicted cognitive flexibility (path e: β = 0.26, SE = 0.07, P < 0.001), and cognitive flexibility predicted mathematics (path i: β = 0.44, SE = 0.12, P < 0.001).

Multiple mediation model for grammar, spelling, and vocabulary. Similarly, cardiorespiratory fitness predicted grammar, spelling, and vocabulary grades (β = 0.21, SE = 0.05, P = 0.013) before considering executive functions as mediator in the model. This direct path decreased to a nonsignificant level (β = 0.11, SE = 0.08, P = 0.191) when the multiple mediation

TABLE 3. Pearson correlations between the variables included in the multiple mediation models.

	Age	SES	CRF	INH	WM	CF	CEF	Math	GSV	TCE
Age	1									
SES	0.13	1								
CRF	0.03	0.17*	1							
INH	0.35**	0.07	0.14	1						
WM	0.33**	0.09	0.25**	0.76**	1					
CF	0.31**	0.16*	0.27**	0.70**	0.78**	1				
CEF	0.38**	0.01	0.12	0	0	0	1			
Math	–0.28**	0.13	0.23**	0.14	0.21*	0.30**	0.05	1		
GSV	–0.24**	0.10	0.19*	0.17*	0.23**	0.32**	0.03	0.93**	1	
TCE	–0.12	0.12	0.11	0.27**	0.31**	0.36**	0.05	0.77**	0.88**	1

*P < 0.05.
**P < 0.01.
SES, socioeconomic Status; CRF, cardiorespiratory fitness, INH, inhibition; WM, working memory; CF, cognitive flexibility; CEF, common EF; GSV, grammar, spelling, and vocabulary; TCE, text comprehension and expression.

model was tested. Furthermore, the total effect on grammar, spelling, and vocabulary was significant ($\beta = 0.23$, SE = 0.09, $P = 0.007$, $R^2 = 0.26$), which was explained by the global indirect effect through executive function components ($\beta = 0.12$, SE = 0.03, $P < 0.001$). The specific indirect path through cognitive flexibility (path ei: $\beta = 0.12$, SE = 0.04, $P = 0.008$) drove this effect. Cognitive flexibility was the only component of executive functions that predicted grammar, spelling, and vocabulary grades (path i: $\beta = 0.45$, SE = 0.13, $P = 0.001$), after taking into account the effect of all components.

Multiple mediation model for text comprehension and expression. The direct path from cardiorespiratory fitness to text comprehension and expression, without executive functions in the model, was nonsignificant ($\beta = 0.12$, SE = 0.04, $P = 0.182$). As the direct path between the predictor and the dependent variable was not significant before including executive functions in the model, we did not go forward with mediation analysis.

DISCUSSION

The main objectives of the present study were to reproduce the hypothesized relationship between cardiorespiratory fitness and (a) school grades and (b) executive functions in a large sample of 8- to 12-yr-olds. Furthermore, we investigated (i) the role of executive functions, construed as a four-component system, on this relationship; (ii) whether executive function components may contribute differently to this process; and (iii) whether this relationship is specific to certain school topics.

First, we confirmed the hypothesized relationship between cardiorespiratory fitness and school grades in this sample of 8- to 12-yr-olds. Simple Pearson correlations indicated a positive link between cardiorespiratory fitness and grades in mathematics as well as between cardiorespiratory fitness and grades in grammar, spelling, and vocabulary. By contrast, grades in text comprehension and expression were rather weakly linked with cardiorespiratory fitness. This pattern of results is aligned with a recent meta-analysis documenting a link between cardiorespiratory fitness and mathematics as well as language/reading (5). The present study further suggests the need to distinguish within language school grades, on the one hand, (i) academic performance related to the structure of language such as grammar, vocabulary, or sentence-level language processing and, on the other hand, (ii) text comprehension, oral expression, or language as a communication tool. That some aspects of language grades were predicted by cardiorespiratory fitness but not others is in line with several previous studies (5,35).

Second, the present study also addresses the emerging literature on the link between cardiorespiratory fitness and executive functions. Cardiorespiratory fitness was associated with working memory and cognitive flexibility skills with only a trend for a positive relationship with inhibition. Our results are consonant with the meta-analysis published by de Greef et al. (13), who showed that PA programs enhanced working memory and cognitive flexibility, with only a nonsignificant trend on inhibition. Other works have, however, documented a link between PA and inhibition (9–11). Some inconsistencies may be explained by the variety of forms that inhibition can take (i.e., perceptual interference and response inhibition). In the present work, the latent construct of inhibition represents the common variance to different forms of interference control as well as to proper withholding of response. Yet, such a latent variable approach, which avoids the task impurity problem, remains rare in the literature. Furthermore, the relationship between cardiorespiratory fitness and inhibition might be moderated by age, with reports of a stronger effect in samples younger than the one under study here (36). Overall, the present work is well aligned with the documented link between PA and executive functions, especially when it comes to working memory and cognitive flexibility.

Third, Pearson correlations confirm that executive function skills are associated with performance at school. Inhibition was related to language grades, whereas working memory and cognitive flexibility were related to grades in the two language topics as well as mathematics. These results are not surprising given the well-documented association between executive functions and scholastic performance (7,8,14). As in a recent meta-analytic review that examined the relationship between executive functions and academic achievement (8), inhibition was less associated with school performance than cognitive flexibility and working memory. Interestingly, the bifactor model that we used included a common factor between the nine tasks. This common factor was not related to any of the school topics nor cardiorespiratory fitness despite being clearly dependent on age as expected from a cognitive variable. Interpreting what psychological process(es) the common factor from bifactor models may represent remains very challenging (37); yet, these results point to a significant source of variance across all the tasks that does not relate to cardiorespiratory fitness nor school performance and, thus, could be one source of inconsistency in the field if not properly controlled.

The first step of our mediation analyses examined the direct path between cardiorespiratory fitness and school grades while controlling for age, without including executive functions as a mediator. We verified that, as in the simple regressions, cardiorespiratory fitness predicted grades in (i) mathematics and (ii) grammar, spelling, and vocabulary, but not in (iii) text comprehension and expression. Of note, our separate mediation analyses showed a global indirect effect of the different components of executive functions, explaining in part the link between cardiorespiratory fitness and mathematics as well as between cardiorespiratory and grammar, spelling, and vocabulary. These results are consonant with Schmidt et al. (16), who showed that a single latent factor estimating executive functions mediated the effect of motor ability on scholastic performance. The three different tasks used by Schmidt et al. (16) to build this single factor were reaction time-based tapping inhibition, updating in working memory, and cognitive flexibility. Van der Niet et al. also showed that a common executive function latent factor mediated the link between physical fitness and scholastic performance (17). Their single factor was derived solely from a cognitive flexibility and a planning task. It remains unclear how the single executive functions construct of Schmidt et al. (16) and Van der Niet et al. (17) relate to each other, as well as how representative each may be of executive functions as understood in the field. A departure from this pattern of results is that of Aadland et al. (15), where several fitness and PA indices (e.g., aerobic fitness, MVPA, aiming, and catching) did not predict performance on executive function tasks, represented by a common factor. These authors, therefore, concluded that a common executive function factor does not mediate the link between PA and scholastic performance. A plausible explanation for the results of Adlaand et al. might be the use of paper–pencil tests to evaluate not only working memory but also inhibition and cognitive flexibility. By not measuring RT for these latter two constructs, Aadland et al. may have been less sensitive to individual differences in executive functions. To address these various issues, the present study used a battery of nine tasks, including three different tasks for each of the inhibition, working memory, and cognitive flexibility constructs. Not only were reaction time tasks used for inhibition and cognitive flexibility, but we also combined response speed and accuracy in a measure known as inverse efficiency to best capture speed–accuracy tradeoffs (29). Thus, using RT-based executive function measures, as well as working memory capacity, Schmidt et al. (16), Van der Niet et al. (17), and the current study converge on the role of executive functions in explaining the relationship between PA and scholastic performance. This role remains modest in size, with a beta on the order of 0.12 in our study, and slightly higher in other studies, $\beta = 0.30$ (16) and $r = 0.41$ (17). Interestingly, this result appears to hold despite the use of different fitness measures related to PA.

The novelty of this work, which goes one step beyond previous studies, is the multitasks and multiexecutive function components approach. The multiple mediation model used presents a statistical framework that disentangles the executive functions mechanisms explaining scholastic performance in relation to cardiorespiratory fitness. The findings of the present study suggest that the executive function components differentially contribute to this relationship. The global indirect effect from executive function components on (i) mathematics and (ii) grammar, spelling, and vocabulary was mostly driven by cognitive flexibility. That is, inhibition, working memory, and a common factor to all tasks contributed to some extent to the global indirect effect; however, cognitive flexibility was the only significant mediator when the effects of all components were taken into account. The existing literature suggests that inhibition is associated with a lower extent with PA focused on enhancing cardiorespiratory fitness (13) and scholastic performance (8) than are working memory or cognitive flexibility, which is in agreement with the low contribution of inhibition in the present study.

The present work identifies cognitive flexibility as the key executive function component explaining, at least partially, the relationship between cardiorespiratory fitness and school grades in 8–12 yr old. The special role of cognitive flexibility, over working memory, is worth considering in the context of the existing literature. The executive function literature suggests that cognitive flexibility is the latest to mature among the three core executive function components (6,38). Accordingly, the meta-analytic study by Karr et al. (38) indicates that, during early childhood, executive functions tend to have a unidimensional structure as its components have not differentiated yet. Then as children reach middle childhood, inhibition and working memory tend to differentiate as separated constructs earlier than cognitive flexibility. As the latest executive functions to mature, cognitive flexibility in 8–12 yr old may remain a limiting factor in scholastic performance and, thus, the strongest mediator among the different components. This view predicts that its unique contribution should be age dependent, a proposal worth exploring in future studies. The stronger indirect effect of cognitive flexibility over working memory may also be related to the type of tasks used. In the present work, cognitive flexibility was measured with time-based tasks, unlike working memory, which was evaluated in terms of capacity, and thus avoided reaction time-based tasks. Indeed, speeded measures are often considered a potential confound when measuring working memory capacity (for a review, see Wilhelm et al. [39]). It is possible that individual differences may be more finely captured by time-based tasks than capacity measure tasks, leading to a stronger mediating effect of cognitive flexibility. Future studies that use finer measures of working memory capacity than just span length or list recall, such as the K factor, would be a welcome addition to the field.

The indirect effect of executive functions observed in the present study suggests a mediating role on this relationship. This interpretation is based on the results of previous longitudinal and experimental studies, which have shown that an increase in cardiorespiratory fitness is associated with enhanced executive functioning and scholastic performance (11,13). However, to establish a cause–effect relationship regarding the mediating role of executive functions, the field requires longitudinal and experimental studies that address this question. Such studies should consider using (i) a multitask approach to measure executive functions and (ii) latent variable procedures to unpack the cognitive mechanisms that mediate the relationship between cardiorespiratory fitness and scholastic performance.

Finally, this work is not exempt of limitations. First, this study combines features of a cross-sectional and a prospective design, which does not afford causal inference. Second, data collection was conducted in schools, which did not allow for a direct measure of cardiorespiratory fitness. Nevertheless, the multistage fitness test is the most popular indirect measure of cardiorespiratory fitness and a reliable measure for group testing outside the laboratory (40). Third, school grades were provided by schoolteachers, and the sample is composed of children from different schools; therefore, we cannot assure that the difficulty of the school tests was the same across schools and that school grades may not be subject to bias. The use of standardized tests may be a more reliable measure; however, we did not have access to a standardized test for all the age-groups that participated in the study. Lastly, approximately 25% of the final sample (n = 182) had missing data. However, our results remained the same when only including participants with complete data ($n = 132$), which suggests that this quarter of the sample is not systematically different from the remainder of the sample. We note that these limitations mostly reflect the reality of data collection outside the laboratory, but also when studying school-age children, which are common to the field. A strength of our approach has been to attempt to overcome such limitations via the use of a rich battery of tasks and measures combined with robust statistical methods, such as latent variable procedures, which have several benefits over more traditional approaches, including increased power and better accommodation of missing data. Furthermore, by statistically removing the error variance from several imperfect measures, we were able to keep only the shared variance among all measures, representing more stable latent constructs of interest and thus more reliable measurement of cardiorespiratory fitness, executive functions, and school grades than if we had used single measure for each of these variables (34).

In conclusion, to investigate whether executive functions may explain the link between cardiorespiratory fitness and scholastic performance, we developed a multitask battery assessing each executive function component—inhibition, working memory, and cognitive flexibility—each with three separate tasks. Although inhibition, working memory, and cognitive flexibility correlated with grades in mathematics and language, the latter was the one executive function component explaining, in part, the relationship between children's cardiorespiratory fitness and grades in (i) mathematics and (ii) grammar, spelling, and vocabulary. The present study not only shows the importance of considering separately the different aspects of executive functions in unpacking the relationship of cardiorespiratory fitness to school grades but also gives insight into which cognitive mechanisms may best explain scholastic performance.

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The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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