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Title Page

How physical activity, fitness and motor skills contribute to math performance: Working memory as a mediating factor

Original Investigation

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Competing interests

The authors declare no conflict of interest.

Authors' contributions

HJS and THT contributed to study design and recruitment. JK and HH conducted accelerometer-based physical activity measurements and data analysis. LJ contributed to fitness measurements and VI and PR to cognitive measurements. HJS and AK conducted statistical analysis and wrote the first draft of the manuscript. CHH contributed to the manuscript with his expertise related to the topic. All authors contributed to the interpretation of the results and helped to improve manuscript. All authors have read and approved the final version of the manuscript.

Availability of data

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ABSTRACT

PURPOSE: The purpose of this study was to examine whether physical activity, fitness and motor skills have indirect association with math performance via cognitive outcomes and if so, through which aspects of cognition? **METHODS**: This study comprised 311 6^{th}–9^{th} grade adolescents (12–17y [M age=14.0y], 59% girls) from seven schools throughout Finland in 2015. Math performance was measured via a teacher-rated math achievement and the Basic Arithmetic test. Cognitive functions were measured by broad cognitive test battery. Physical activity was assessed with a self-reported questionnaire and a hip-worn accelerometer. Aerobic fitness was estimated using a maximal 20-m shuttle run test, muscular fitness with curl-up and push-up tests, and motor skills with a 5-leaps test and a throwing-catching combination test. Structural equation modeling was applied to examine the associations. **RESULTS:** In both boys and girls, motor skills had a positive indirect association with math outcomes through visuospatial working memory. Among girls, muscular fitness had a positive indirect association with math outcomes through visuospatial working memory. Aerobic fitness was positively associated with math achievement, but the indirect path via cognition was not observed. Self-reported physical activity had a borderline indirect positive association with math outcomes through visuospatial working memory. Accelerometer-based physical activity did not correlate with math performance. **CONCLUSION:** Motor skills and muscular fitness had indirect, positive associations with math performance, mediated by visuospatial working memory. The results give support to the viewpoints that the connections between motor skills, fitness and physical activity to academic skills are mediated via specific cognitive skills.

Key words: adolescents, motor skills, physical fitness, working memory

1 INTRODUCTION

Internationally, a lack of interest towards mathematics continues to rise.[1] Difficulties in math learning are common, and for example two thirds of children in the United States have difficulties to achieve the expected level of performance in both 4th and 8th grades.[2] Even in countries, where overall achievement in mathematics are higher, 6% of children have mathematics learning disabilities, and 26% have persistently low achievement in mathematics.[3] Math skills are considered to be crucial for success in Western societies, and severe numeracy difficulties may have a serious impact on occupational and social opportunities.[2,4]

Being physically active and fit is known to benefit brain health and function, and is especially beneficial for cognitive function and academic performance.[5] A growing body of literature has shown positive associations of physical activity and fitness with math performance.[6,7] Further, the association between aerobic fitness and cognition, particularly executive functions, has been found to be robust.[5] However, less is known about the associations of muscular fitness and motor skills with cognitive function and academic performance.[8] Recently, more attention has been focused on motor skills, since it has been suggested that coordinative, cognitively engaging forms of exercise may also have effects on cognition along with less cognitively engaging forms of exercise.[9,10]

Executive function is defined as a group of higher-order cognitive processes involved in self-regulatory and goal-directed actions, and is a strong predictor of academic performance.[11] In particular, mathematics performance relies heavily on working memory, but also on other core executive functions, such as inhibition and mental flexibility.[4] Working memory is defined as the ability to hold and manipulate information in mind; inhibition is defined as the ability to suppress distracting information and unwanted responses; and mental flexibility refers to the ability to flexibly shift between mental states, rule sets or tasks.[11] Furthermore, other aspects of cognition, such as sustained attention and fluid reasoning (i.e., the ability to think logically and problem solve in novel environments), which are associated with executive functions, have been shown to relate to math performance.[12,13] Likewise, visuo-spatial skills, especially spatial visualization, have been found to both correlate and predict the development of math skills.[14]

It has been suggested that there is a need for further exploration of the mediators of physical activity and academic performance.[6] Many theories about underlying mechanisms have been posited, for example biological and psychosocial theories as well as embodied learning theories, which suggest that physical activity improves cognition via multiple, different pathways and through that, academic performance.[6,10] However, to date, the mediating role of cognitive functions (mainly executive functions) between physical activity[15,16]/ physical fitness[17–19]/ motor skills[20,21]/ aerobic fitness[22,23] and academic performance is not heavily studied. That is, only couple of studies have assessed the mediating effects on mathematics.[17,23,24]

The purpose of this study was to examine whether physical activity, fitness or motor skills have indirect associations with mathematics performance through cognitive functions, and if so, through which aspects of cognition? We hypothesized that physical activity, fitness and motor skills are positively associated with cognitive functions and mathematics performance, and that the association with mathematics are mediated by cognitive functions, with a particular focus on executive functions.

2 METHODS

2.1 Study population

The participants were recruited in two waves. First, 805 students participating in a larger study regarding the national "Finnish Schools on the Move" program were invited to participate in this study during spring 2015.[8] One hundred sixteen students from five schools with a wide geographical representation of Finland participated in the study. Second, 484 students from two schools in the Jyväskylä school district in Finland were invited to participate in this study during autumn 2015, with 195 students agreeing to participate. Children, who needed specialized support with individualized educational plan, were excluded from the analyses. Altogether, this study comprised 311 6th–9th grade students (59% girls) from seven schools throughout Finland. Both the students and their guardians gave written informed assent/consent to participate. The study protocol was approved by the Ethics Committee of the University of Jyväskylä.

2.2 Math performance

The math performance was assessed from two different perspectives. The education services provided students' math achievements from the register. The scale for this teacher-rated numerical evaluation was 4–10, where four denotes failure and 10 denotes excellent knowledge and skills. This comprehensive evaluation is based on teacher's continuous monitoring of the classroom behaviour and multiple curriculum-based exams, and it tries to catch the overall level of the mathematical skills in various types of curriculum-based math contents. Basic arithmetic skills were determined with the Basic Arithmetic Test,[25] including addition, subtraction, multiplication and division tasks. Students were asked to perform as many problems as possible within a 3-minute time limit. The number of correct answers were used to illustrate arithmetic skills. This test measures the basic skills learned at the early grades. In addition, it measures rapid retrieval of facts and mental calculations algorithms from long-term memory. The test was conducted in a quiet group session under the guidance of two educated research personnel.

2.3 Cognitive functions

A battery of cognitive functions was measured, which included a modified flanker task, four tests (Paired Associates Learning (PAL), Spatial Working Memory (SWM), Reaction Time (RTI) and Rapid Visual Information Processing (RVP)) from the Cambridge Neuropsychological Test Automated Battery (CANTAB) (CANTAB eclipse version 6, Cambridge Cognition, Cambridge, UK), four tests, one from each main indexes (Similarities, Matrix Reasoning, Digit Span, and Coding) from the Wechsler Intelligence Scale for Children (WISC-IV), and the Spatial Relations subtest from the Woodcock-Johnson test battery. The modified flanker task and CANTAB tests were assessed with tablets (Dell Venue 11 Pro 7130, screen 10.8", processor: Intel® Core™ i5-4300Y CPU 1.60 GHz, Memory (RAM): 4.00 GB, System type: 64-bit, x64-based processor), while WISC tests and Spatial Relations subtest were measured with pen and paper. A flanker task, four CANTAB tests, and two WISC tests (Similarities and Digit Span) were run individually in a sound-attenuated location with the guidance of trained research assistants and in accordance with the standard instructions. The test battery took about 45 minutes to complete. The Spatial Relations subtest and two WISC tests (Coding and Matrix Reasoning) were assessed together with the arithmetic test in a small group session under the supervision of two trained research assistants. This session took about 30 minutes to complete.

A modified version of the Eriksen flanker task[26] was used to assess attentional inhibition. From the CANTAB test battery, the PAL test assessed visual memory, the SWM test assessed visuospatial working memory, the RTI test assessed reaction and movement times to visual stimulus, and the RVP test assessed sustained attention. Due to several variables produced by the flanker task and each CANTAB tests, the principal component analysis (according to Rovio et al.[27]) was conducted separately for each individual test to reduce the number of variables and to identify components accounting for most of the variation within the cognition data set. The weights for the observed items of the cognitive tests used to create the principal components are presented in Supporting information table S1. Each component represented the performance in a particular cognitive test and were normalized based on the rank order normalization procedure, producing variables with mean value of 0 and a standard deviation of 1.

From the WISC test battery, the Similarities test assessed verbal concept formation and verbal abstract reasoning, the Matrix Reasoning test assessed fluid reasoning, the Digit Span test assessed auditory verbal working memory and the Coding test assessed processing speed. For each of these WISC tests, the number of correct answers (raw scores of standardized scores) were calculated to represent performance. The Spatial Relations subtest is a subtest from the Woodcock and Johnson [28] test battery measuring spatial visualization ability. The number of correctly solved items within three-minute time limit was calculated to represent spatial visualization ability. The cognitive tests are described in more detail in 1.1 Cognitive functions in Supporting information file.

2.4 Physical activity

Physical activity was self-reported by a questionnaire and measured by a hip-worn accelerometer. Self-reported physical activity was assessed with the question used in Health Behaviour in School-aged Children survey.[29] The question assessed self-reported physical activity with moderate-to-vigorous intensity by asking how many days participants were physically active for a total of at least 60 minutes per day during a typical week. The response categories were as follows: 0 days, 1 day, 2 days, …7 days. A short description of moderate-to-vigorous physical activity (MVPA) and examples assisted in answering the question. Accelerometer-based physical activity was measured with GT3X+ and wGT3X+ accelerometers (Pensacola, Florida, USA) worn on the right hip during waking hours for seven full, consecutive days. Bathing or other water-based activities were excluded. Data were collected in raw 30 Hz acceleration standardly filtered and converted into 15-s epoch counts. Data reduction was made with a customized Visual Basic macro for Excel software. For a valid monitoring period, readings including at least 500 min/day measured between 7:00 am and 11:00 pm on three days were required.[30] Non-wear time was defined as periods of 30 min of consecutive zero counts and spurious accelerations (over 20,000 counts per minute (cpm)) were ruled out.[31] Participants' average device wearing time was 782 min (SD=49) per day. Evenson et al.'s[32] cut-points were used to calculate MVPA (≥2296 cpm).

2.5 Physical fitness and motor skills

Aerobic fitness, muscular fitness and motor skills were measured in small group sessions with the tests included in the Move! - monitoring system for physical functional capacity.[33] Aerobic fitness was estimated with a 20-m shuttle run test, where running speed was gradually increased with 1-minute intervals until maximal voluntary exhaustion. Results of the test were the number of laps run. Muscular fitness was determined via the sum of abdominal and upper-body muscle strength. Abdominal strength was measured with a curl-up test, where the number of curl-ups performed (maximal number of repetitions limited to 75) was calculated as the test result. Upper-body muscle strength was measured with a push-up test with slightly different technique for boys and girls; boys had hands and toes on the ground and girls had hands and knees on the ground. The test result was the number of push-ups performed during a 1-minute period. Motor skills were determined via the sum of the performance in a 5-leaps test and a throwing-catching combination test. In the 5-leaps test, students performed five consecutive leaps with the instruction to jump as far as they can. The test result was the length of the performance recorded with 0.1 m accuracy. In the throwing-catching combination test, students performed an overhand throw of a tennis ball from a set distance to a target placed on the wall and then caught the ball after one bounce. The test result was the number of correctly performed attempts out of 20. All results of the tests were standardized according to sex and age group. The measurements are described in more detail in the study of Joensuu et al.[33]

2.6 Confounding factors

Pubertal stage was assessed via a self-assessment questionnaire answered by students and categorized according to the Tanner puberty stage.[34] Body fat percentage was measured via body composition analyzer InBody 720. Students' learning difficulties and mother's education were assessed via a web-based survey completed by a parent or guardian. The questions were as follows: ''Does your child have any diagnosed learning difficulties?'' (categorization, yes (1) and no (0)). "What is the level of mother's education?" (categorization, tertiary level education (1) and basic or upper secondary education (0)).

2.7 Statistical analysis

The descriptive statistics were calculated by using SPSS 25.0 for Windows (SPSS Inc., Chicago, IL, USA), and all further analyses were conducted using Mplus statistical package (Version 7, Los Angeles, CA, USA).[35] The descriptive statistics are presented as means and standard deviations or percentages (%). Differences in the study variables between girls and boys were tested via Student's t-test or Pearson's chi-squared test. As preliminary analysis, the sample correlation coefficients among the study variables were estimated among all and separately among boys and girls.

To study associations of physical activity/fitness/motor skills on cognitive functions and math performance, as well as the mediating role of cognitive function in the relationship between physical activity/fitness/motor skills and math performance, path modeling within structural equation modeling framework was utilized. All regressions were adjusted for potential confounding variables, including age, sex, pubertal stage, body fat percentage, learning difficulties and mother's education. First, the direct associations of physical activity/fitness/motor skills on cognitive function/math performance were modelled by using linear regression. Second, a mediator model, including one cognitive function as a mediator at a time, was estimated (see Figure 1). The model included indirect paths from physical activity/fitness/motor skills to both outcomes of math performance (arithmetic skills and teacher-rated math performance) through a cognitive test. The math performance outcomes were allowed to correlate.

The Satorra-Bentler scaled χ^2-test, the comparative fit index (CFI), the Tucker-Lewis Index (TLI), the root mean square error of approximation (RMSEA), and the standardized root-mean-square residual (SRMR) were used to evaluate the goodness-of-fit of the models. The model fits the data well if the P-value for the χ^2-test is non-significant, CFI and TLI values are close to 0.95, the RMSEA value is below 0.06, and the SRMR value is below 0.08 (Hu & Bentler 1999). If the model did not fit the data adequately well, the direct effects from physical activity/fitness/motor skills to math score or teacher-rated math performance were additionally estimated. Indirect effects of interest were calculated as a product of the regression coefficients ($a \times b1$, $a \times b2$) and tested for significance. When the interaction term [physical activity/fitness/motor skills × gender (girl)] was needed to add in the model, the indirect effects were calculated separately for girls and boys by using the parameters of the model (boys: $a \times b1$, $a \times b2$; girls: $(a+i1) \times b1$, $(a+i1) \times b2$). To control for Type 1 error rate the significance level of the study was set at 0.01.

More information about linear regression models and technical details of the modeling are provided in the Supporting information file (see 1.2.1 Linear regression models and 1.2.2 Technical details of the modeling).

3 RESULTS

Sex-specific distributions and gender differences in observed variables are presented in Table 1.

3.1 Mediator models

Because accelerometer-based PA did not correlate with math performance, no further modeling was conducted. In addition, performance on the RTI test did not correlate with math performance, and the association of Digit span with math performance was attenuated after adjusting for confounding variables. Therefore, these cognitive functions were not considered as mediating variables in the modeling.

The mediator models including only the indirect associations of self-reported PA on math performance through a cognitive outcome (SWM, RVP, Matrix reasoning and Coding test) fitted the data well, indicating that the association was fully mediated through each cognitive function (see Table S6). The mediator models for aerobic fitness (SWM and Similarities test as mediators), muscular fitness (flanker task, SWM, RVP and Spatial relations tests as mediators) and motor skills (flanker task, PAL, SWM, RVP, Similarities, Matrix reasoning and Spatial relations test) including only the indirect effects did not fit the data adequately well, and therefore the direct effects from aerobic fitness on math performance were additionally estimated (see Table S6).

The estimation results of the mediator models are presented in Table 2 and Table 3 (see also Figure 1).

3.2 Indirect associations

The estimated unstandardized indirect associations are presented in Tables 4 and 5. Of the cognitive outcomes, which were associated with both math performance and physical activity/fitness/motor skills, SWM mediated the associations of muscular fitness and motor skills with math performance at a significance level of 0.01. Muscular fitness had a positive indirect association with both teacher-rated math achievement and arithmetic skills through performance in the SWM test among girls (unstandardized indirect association b=0.06, p=0.003; b=0.17, p=0.003, respectively). In addition, motor skills had a positive indirect association with both teacher-rated math achievement and arithmetic skills through performance in the SWM test among all children (b=0.07, p=0.001; b=0.19, p<0.001, respectively).

Several cognitive functions appeared to mediate the associations at the significance level of 0.05 but these associations did not reach significance at the 0.01 level. Self-reported physical activity had a positive indirect association with both teacher-rated math achievement and arithmetic skills through performance in the SWM test among all children (b=0.04, p=0.014; b=0.10, p=0.016, respectively). In addition, among boys, self-reported physical activity had a positive indirect association with both teacher-rated math achievement and arithmetic skills through performance in the RVP test (b=0.07, p=0.022; b=0.23, p=0.021, respectively) and Matrix reasoning test (b=0.06, p=0.043; b=0.13, p=0.036, respectively).

Aerobic fitness had a negative indirect association with teacher-rated math performance through performance in the Similarities test among boys (b=-0.08, p=0.047). Muscular fitness had a positive indirect association with both teacher-rated math achievement and arithmetic skills through performance in the RVP test among all children (b=0.04, p=0.043; b=0.14, p=0.047, respectively).

Motor skills had a positive indirect association with both teacher-rated math achievement and arithmetic skills through performance RVP test (b=0.04, p=0.023; b=0.13, p=0.023, respectively) and Matrix reasoning test (b=0.04, p=0.038; b=0.11, p=0.042, respectively) among all children. In addition, motor skills had a positive indirect association with arithmetic skills through performance on the flanker task (b=0.09, p=0.023) and PAL test (b=0.07, p=0.046) as well as with teacher-rated math achievement through performance in the Spatial relations test (b=0.04, p=0.030). Furthermore, among boys, motor skills had a negative indirect association of with both arithmetic skills and teacher-rated math achievement through performance on the Similarities test (b=-0.06, p=0.017; b=-0.17, p=0.020, respectively).

3.3 Supporting results

The correlation coefficients for study variables among all children are presented in the supporting Table S2 and separately for boys and girls in the supporting Table S3. The estimation results of the linear regression models for the direct associations of physical activity, fitness and motors skills with cognitive and math outcomes are presented in the supporting information file (the chapter 2.1 Direct associations) and Tables S4 and S5. These associations were adjusted for age, sex, pubertal stage, body fat percentage, learning difficulties and mother's education. The model-fit of the mediator models are presented in supporting Table S6.

4 DISCUSSION

4.1 Main findings

This study examined whether physical activity, fitness or motor skills have indirect associations with mathematics performance through cognitive functions, and if so, through which aspects of cognition. The present results indicate that muscular fitness and motor skills had a positive indirect association with math achievement and arithmetic skills through visuospatial working memory. In addition, several other cognitive functions (e.g. sustained attention and fluid reasoning) appeared to mediate the associations at the significance level of 0.05, but these associations did not reach significance at the 0.01 level.

4.2 Visuospatial working memory mediating the associations of muscular fitness and motor skills with math performance

The results of this study replicate earlier findings indicating that cognitive functions play a role in mediating the association between physical activity, fitness and motor skills with academic achievement.[15,17–21] This study adds value to the existing literature by showing that visuospatial working memory were the strongest cognitive function mediating the associations of muscular fitness and motor skills with math performance. In addition, even though, different aspects of math performance were assessed, the indirect paths between muscular fitness/motor skills and mathematics via working memory were quite similar.

4.2.1 Working memory

Previous studies examining the association between math performance and executive functions have suggested that among all core executive functions, working memory has the strongest association with mathematical performance, while the roles of inhibition and shifting are less studied and the findings have been mixed.[4] Earlier studies have also suggested that working memory may play a role as a mediator between physical fitness and academic outcomes more often than the other core executive components. De Bruijn et al.[17] showed that working memory mediated the association between physical fitness (a component score of aerobic fitness, muscular strength, running speed and agility and upper-limb agility) and mathematics in eight-year-old children, while inhibition or mental flexibility did not. We replicated these results by showing that, from the executive outcomes assessed, visuospatial working memory, mediated the positive association of muscular fitness and motor skills with mathematics. Furthermore, Núñez et al.[23]

showed that inhibition did not mediate the relationship between aerobic fitness and math fluency, a finding supported herein.

In the study of De Bruijn et al.[17], both verbal and visuospatial working memory performance mediated the association of physical fitness and mathematics. In this study, verbal working memory did not have an association with any physical activity, fitness or motor skills measures (see Table S2), while visuospatial working memory mediated the positive association of muscular fitness and motor skills with mathematics. The present results highlight the role of visuospatial working memory as the mediator between physical activity/fitness/motor skills and mathematics. This might result from the requirements of physical activity/fitness/motor skills components; the ability to process and manipulate visuospatial information is routinely needed when being physically active or performing complex motor skill tasks.

4.2.2 Other aspects of cognition

From the other measured aspects of cognition, sustained attention and fluid reasoning appeared to systematically mediate the indirect associations of self-reported physical activity/muscular fitness/motor skills and math performance at the significance level of 0.05. It seems that, besides working memory, there may be other cognitive functions that may mediate the association of physical activity/fitness/motor skills and math performance. Attentional performance has been related to academic success in mathematics,[12] while fluid reasoning has shown to be important predictor of future math achievement in childhood and adolescence,[13] and explain the development of arithmetic skills.[3] Even though, visuospatial working memory, sustained attention and fluid reasoning are highly correlated, they may have unique contributions to math achievement, which may explain the borderline indirect associations observed.

4.3 Associations of physical activity, fitness and motor skills with math performance

In most previous studies, where cognition mediated the association of fitness and academic achievement, physical fitness components included aerobic, muscular and motor skill specific fitness measures.[17–19] In this study, we wanted to examine these different components separately. Of the measured variables, muscular fitness and motor skills had an indirect association with math performance through cognition. Further, in this study, motor skills were the most systematically associated with academic and cognitive performance. Moreover, even though aerobic fitness had direct positive associations with math and cognitive performance, the indirect path to math via cognition was not observed. Self-reported physical activity was associated with cognitive and math performance and had a borderline positive indirect association with math performance via visuospatial working memory. Accelerometer-based physical activity was not associated with math performance, replicating the results of earlier studies.[7,8,36] The inconsistency between physical activity measures may occur because the measures reflect different contents and constructs of physical activity.[36]

The present results partially replicate those of Schmidt et al.[21], who showed that motor coordination had an indirect association with academic achievement through executive functions. However, aerobic and muscular fitness did not exhibit a similar indirect association.[21] Cadoret et al.[20] showed that motor skills had a positive effect on academic achievement through an indirect path via cognitive ability. Whereas, Núñez et al.[23] showed that the relationship between aerobic fitness and math fluency was not mediated by inhibition. Similarly, Aadland et al.[24] showed that executive functions did not mediate the associations of accelerometer-based physical activity and aerobic fitness with academic achievement, while the association between motor skills and academic performance seemed to be modestly mediated by executive functions. On the contrary, in the study of Visier-Alfonso et al.[22], aerobic fitness had an indirect association with academic achievement through inhibition and cognitive flexibility. As such, the effects of motor skills on academic success appear to be mediated more often by cognition, while the effects of aerobic fitness on academic achievement appear to be mediated by other factors, such as molecular and cellular mediators, structural and functional brain changes and behavioral and socioemotional mediators.[37]

The systematic associations of motor skills with cognitive and math outcomes, and the mediating role of cognitive functions between motors skills and mathematics, may be due to that motor and cognitive skills are developmentally linked.[38,39] Especially, the higher-order cognitive skills are needed to perform complex motor skills, which is supported by the co-activation of the cerebellum and the prefrontal cortex, the brain areas important for complex and coordinated movements and higher-order cognitive skills, respectively.[38] Intervention studies on improving motor coordination could be one method to further explore this relationships between motor skills, working memory and mathematics. To conclude the present results, the mediating role of cognitive functions do not appear to be generalized, but rather more specific depending on physical activity/fitness/motor skills dimensions measured and the academic outcomes used.

4.4 Strengths and limitations

To our knowledge, this is the first study identifying the cognitive functions mediating the associations between physical activity/fitness/motor skills and math performance, including not only executive outcomes, but also other aspects of cognition. Further, we used a relatively large range measures of physical activity, fitness and motor skills instead of a combined fitness outcome. Moreover, several important confounding factors were considered, and a comprehensive analytical approach employing structural equation modelling was used. The major limitation herein was the cross-sectional nature of the study, and there remains a need for intervention studies to confirm these results. In addition, the participation rate in the first five schools of recruitment was low because these students had been involved in a larger study for two years and did not want to participate in additional measurements. For that reason, two new schools were recruited, and the participation rates were adequate in those schools. Furthermore, the sample size is small for the number of cognitive assessments and therefore, the statistical power to detect small-sized indirect associations may be insufficient. To decrease the probability of a Type I error due to multiple tests, we used a more stringent alpha level ($\alpha = 0.01$) for interpretation of the results. Several cognitive outcomes mediated the associations at the alpha level of 0.05, but not at 0.01. Studies with larger sample sizes are required to verify these indirect associations. Lastly, physical fitness and maturation were estimated, rather than directly measured, which may partly explain the results.

4.5 Perspective

Physical activity and fitness are known to benefit cognitive function and academic performance.[5] Since the need for clarifying the mediators between physical activity and academic performance has been acknowledged[6], the results of this study provide important novel information on the mediating role of spatial working memory between the positive associations of muscular fitness, motor skills and math performance. The mediating role of cognitive functions appear to be specific depending on physical activity, fitness or motor skills dimensions measured, and which academic outcomes assessed. Furthermore, this study showed that motor skills were the most systematically associated with academic and cognitive performance, which suggests that physical activity including not only aerobic, but also muscular and motor specific domains may benefit math performance.

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Table 1. Sex-specific distributions and gender differences in observed variables

	All (N=310)			Boys (N=127)		Girls (N=183)		
	N	Mean (SD)	Min, Max	N	Mean (SD)	N	Mean (SD)	*p*
Age (years)	310	14.0 (1.1)	12, 17	127	14.1 (1.1)	183	14.0 (1.1)	0.378
Pubertal stage [a]	296	3.4 (0.9)	1, 5	123	3.5 (1.0)	173	3.3 (0.8)	0.031*
Math Performance								
Teacher-rated math [b]	308	8.2 (1.2)	4, 10	126	8.1 (1.1)	182	8.2 (1.2)	0.470
Arithmetic skills [c]	304	14.3 (3.6)	4, 24	123	15.0 (3.6)	181	13.9 (3.6)	0.011*
Cognitive functions								
Inhibition (component) [d]	297	0.0 (1.0)	-3.5, 1.8	122	-0.1 (1.2)	175	0.1 (0.9)	0.041*
Visual memory (component) [e]	305	2.9 (1.0)	-1.3, 4.2	124	2.8 (1.1)	181	3.0 (0.9)	0.086
Visuospatial working memory (component) [f]	305	1.5 (1.0)	-2.1, 3.6	124	1.6 (0.9)	181	1.4 (1.0)	0.105
Attentional reaction time (component) [g]	306	0.0 (1.0)	-3.0, 3.4	125	-0.3 (1.0)	181	0.2 (0.9)	<0.001***
Sustained attention (component) [h]	305	0.0 (1.0)	-4.0, 2.5	125	0.0 (1.1)	180	0.0 (0.9)	0.724
Verbal reasoning [i]	305	29.0 (4.0)	16, 37	125	28.7 (4.1)	180	29.2 (3.9)	0.260
Fluid reasoning [j]	304	26.3 (3.4)	14, 34	124	26.2 (3.6)	180	26.4 (3.3)	0.585
Auditory verbal working memory [k]	305	15.3 (2.9)	10, 25	125	15.3 (3.0)	180	15.3 (2.9)	0.961
Processing speed [l]	304	58.7 (13.5)	28, 99	124	56.7 (13.1)	180	60.1 (13.7)	0.033*
Spatial visualization [m]	304	21.4 (2.7)	9, 28	123	21.3 (2.6)	181	21.5 (2.8)	0.444
Physical activity								
Self-reported PA [n]	305	4.7 (1.9)	0, 7	124	5.0 (1.9)	181	4.4 (1.9)	0.018*
Accelerometer-based PA [o]	237	47.9 (21.0)	13.9, 133.2	86	54.1 (22.8)	151	44.4 (19.1)	0.001**
Fitness								
Aerobic fitness (standardized) [p]	268	0.0 (1.0)	-2.5, 2.3	112	0.0 (1.0)	156	0.0 (1.0)	0.988
Aerobic fitness [q]	268	49.0 (20.8)		112	58.9 (21.3)	156	41.9 (17.2)	<0.001***
Muscular fitness (standardized) [r]	264	0.0 (1.7)	-3.7, 4.5	109	0.0 (1.7)	155	0.0 (1.7)	0.867
Abdominal strength [s]	280	45.9 (22.8)		117	51.7 (23.0)	163	41.7 (21.8)	<0.001***
Upper-body muscle strength [t]	270	25.8 (13.4)		112	23.6 (13.8)	158	27.5 (12.9)	0.018*
Motor skills (standardized) [u]	276	0.0 (1.7)	-5.5, 3.4	114	0.0 (1.7)	162	0.0 (1.6)	0.979
Locomotor skills (a 5-leaps test) [v]	279	9.2 (1.2)		115	9.7 (1.3)	164	8.9 (1.0)	<0.001***
Manipulative skills (a throwing-catching combination test) [w]	286	12.9 (4.8)		118	14.0 (4.7)	168	12.2 (4.8)	0.002**
Body fat percentage (%) [x]	295	19.0 (8.3)	3.0, 49.8	122	13.8 (6.8)	173	22.6 (7.2)	<0.001***
Learning difficulties (yes) [y]	220	6.4 %		93	8.6 %	127	4.7 %	0.244
Mother education (tertiary level education) [z]	222	83.8 %		97	84.5 %	125	83.2 %	0.789

P value for gender differences (Student's t-test or Pearson's chi-squared test), *$p < 0.05$, **$p < 0.01$, *** $p < 0.001$.

[a] Pubertal stage, based on self-assessment questionnaire and categorized according to the Tanner puberty stage, range 1–5.

[b] Teacher-rated math achievement (a scale of 4–10, where 4 denotes a failure and 10 denotes excellent knowledge and skills).

[c] Arithmetic skills, the Basic Arithmetic Test including addition, subtraction, multiplication and division tasks, the number of correct answers

[d] Inhibition, a modified flanker task (the component score formed from response accuracy (%) and reaction time for correct answers (ms) for congruent and incongruent trials, and the interference score for response accuracy (congruent – incongruent))

[e] Visual memory, the Paired Associates Learning (PAL) test from the CANTAB test battery (the component score formed from PAL First trial memory score, PAL Mean errors to success, PAL Mean trials to success, PAL Number of patterns succeeded on, PAL Stages completed, PAL Stages completed on first trial, PAL Total errors, PAL Total errors (adjusted), PAL Total trials, PAL Total trials (adjusted), PAL Total errors (6 shapes, adjusted) and PAL Total errors (8 shapes, adjusted))

[f] Visuospatial working memory, Spatial Working Memory (SWM) test from the CANTAB test battery (the component score formed from SWM Between errors, SWM Between errors (4 boxes), SWM Within errors, SWM Within errors (4 boxes), SWM Total errors, SWM Total errors (4 boxes), SWM Strategy, SWM Mean time to first response, SWM Mean time to last response and SWM Mean token-search preparation time)

[g] Attentional reaction time, Reaction Time (RTI) test from the CANTAB test battery (the component score formed from RTI Mean simple reaction time, RTI Mean simple movement time, RTI Simple accuracy score, RTI Simple error score (all), RTI Mean five-choice reaction time, RTI Mean five-choice movement time and RTI Five-choice accuracy score)

[h] Sustained attention, Rapid Visual Information Processing (RVP) tests from the CANTAB test battery (the component score formed from RVP A', RVP B'', RVP Probability of false alarm, RVP Probability of hit, RVP Mean latency, RVP Total correct rejections, RVP Total false alarms, RVP Total hits, RVP Total misses)

[i] Verbal reasoning, Similarities test from the WISC test battery (the number of correct answers (raw scores))

[j] Fluid reasoning, Matrix reasoning test from the WISC test battery (the number of correct answers (raw scores))

[k] Auditory verbal working memory, Digit Span test from the WISC test battery (the component score formed from the raw scores for digit span forward and backward)

[l] Processing speed, Coding test from the WISC test battery (the number of correct answers (raw scores))

[m] Spatial visualization, Spatial relations test from the Woodcock-Johnson test battery (The number of correctly solved items)

[n] Self-reported physical activity, how many days children were physically active for a total of at least 60 minutes per day with moderate-to-vigorous intensity during a typical or usual week. The response categories were as follows: 1= 0 days, 2 = 1 day, 3= 2 days, …8 = 7 days

[o] Accelerometer-based physical activity, measured with the ActiGraph accelerometer using a cut-off value 2296 counts per minute indicating moderate-to-vigorous intensity physical activity.

[p] Aerobic fitness, standardized according to sex and age group

[q] Aerobic fitness**,** a maximal 20-m shuttle run test (the number of laps run).

[r] Muscular fitness, the sum of abdominal and upper-body muscle strength standardized according to sex and age group

[s] Abdominal strength, a curl-up test (the number of curl-ups performed).

[t] Upper-body muscle strength, a push-up test (the number of push-ups performed).

[u] Motor skills, the sum of the locomotor skills and manipulative skills standardized according to sex and age group

[v] Locomotor skills**,** a 5-leaps test (the length of the performance (m)).

[w] Manipulative skills, a throwing-catching combination test (the number of correctly performed attempts).

[x] Body fat percentage (%), measured via body composition analyser InBody 720.

[y] Leaning difficulties, asked from the main caregiver: Does your child have any diagnosed learning difficulties?'' (categorization, yes (1) and no (0))

[z] Mother's education, asked from the main caregiver: "What is the level of mother's education?" (categorization, tertiary level education (1) and basic or upper secondary education (0)).

Table 2. The estimation results of the mediator models of physical activity/fitness/motor skills on math performance through a computer-assisted cognitive function test.

	Flanker			PAL			SWM			RVP		
	B	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
Self-reported PA → Cognitive function → Math performance												
Cognitive function	- [a]			- [a]								
Self-reported PA, *a*							0.17	0.06	0.004*	0.24	0.10	0.016
Self-reported PA × gender (girl), *i1*							- [b]			-0.43	0.19	0.024
Arithmetic skills												
Cognitive function, *b1*							0.30	0.06	<0.001**	0.49	0.04	<0.001**
Teacher-rated math												
Cognitive function, *b2*							0.34	0.06	<0.001**	0.48	0.04	<0.001**
Muscular fitness → Cognitive function → Math performance												
Cognitive function				- [a]								
Muscular fitness, *a*	0.11	0.06	0.050				0.03	0.09	0.788	0.13	0.07	0.048
Muscular fitness × gender (girl), *i1*	- [b]						0.21	0.10	0.029	- [b]		
Arithmetic skills												
Cognitive function, *b1*	0.30	0.06	<0.001**				0.28	0.06	<0.001**	0.49	0.05	<0.001**
Muscular fitness, *c1*	0.09	0.07	0.158				-0.07	0.09	0.478	0.05	0.06	0.311
Muscular fitness × gender (girl), *i2*	- [b]						0.17	0.09	0.062			
Teacher-rated math												
Cognitive function, *b2*	0.16	0.06	0.012				0.28	0.06	<0.001**	0.37	0.06	<0.001**
Muscular fitness, *c2*	0.26	0.07	<0.001**				0.06	0.10	0.523	0.12	0.09	0.171
Muscular fitness × gender (girl), *i3*	- [b]						0.20	0.09	0.032			
Motor skills → Cognitive function → Math performance												
Cognitive function												
Motor skills, *a*	0.15	0.06	0.011	0.16	0.07	0.020	0.29	0.06	<0.001**	0.12	0.06	0.025
Arithmetic skills												
Cognitive function, *b1*	0.29	0.06	<0.001**	0.20	0.06	<0.001**	0.30	0.06	<0.001**	0.48	0.05	<0.001**
Motor skills, *c1*	0.14	0.07	0.042	0.15	0.07	0.031	- [c]			0.12	0.07	0.067
Teacher-rated math												
Cognitive function, *b2*	0.15	0.06	0.016	0.16	0.06	0.010	0.33	0.06	<0.001**	0.45	0.05	<0.001**
Motor skills, *c2*	0.22	0.07	0.002*	0.21	0.07	0.002*	- [c]			0.18	0.06	0.004*

*$p < 0.01$, **$p < 0.001$.

Note. All the models were adjusted for age, sex, pubertal stage, body fat percentage, mother's education and learning difficulties. The *a, b1, b2, c1, c2, i1, i2 and i3* are the paths in the model (see Figure 1).

[a] There were no significant association between physical activity/fitness and cognitive function based on the correlations/ linear regression models and therefore, no path modeling was conducted. [b] Based on the linear regression models, there was no significant interaction between physical activity/fitness and gender. [c] A mediator model fitted the data adequate well without direct effect of physical activity/fitness/motor skills on math performance.

Abbreviations: B = standardized regression coefficient; PA = physical activity; PAL= Paired Associates Learning; RVP, Rapid Visual Information Processing; SE = standard error; SWM = Spatial Working Memory.

Table 3. The estimation results of the mediator models of physical activity/fitness/motor skills on math performance through a paper and pen measured cognitive function test.

	Similarities			Matrix reasoning			Coding			Spatial relations		
	B	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
Self-reported PA → Cognitive function test → Math performance												
Cognitive function test	-									-		
Self-reported PA, *a*				0.19	0.09	0.034	0.17	0.08	0.049			
Self-reported PA × gender (girl), *i1*				-0.24	0.18	0.199	-0.17	0.18	0.350			
Arithmetic skills	-									-		
Cognitive function test, *b1*				0.38	0.05	<0.001**	0.32	0.05	<0.001**			
Teacher-rated math	-									-		
Cognitive function, *b2*				0.48	0.04	<0.001**	0.28	0.05	<0.001**			
Aerobic fitness → Cognitive function test → Math performance												
Cognitive function test				-			-			-		
Aerobic fitness, *a*	-0.21	0.10	0.034									
Aerobic fitness × gender (girl), *i1*	0.25	0.09	0.005*									
Arithmetic skills				-			-			-		
Cognitive function test, *b1*	0.31	0.06	<0.001**									
Aerobic fitness, *c1*	0.10	0.09	0.286									
Aerobic fitness × gender (girl), *i2*	0.15	0.09	0.081									
Teacher-rated math				-			-			-		
Cognitive function test, *b2*	0.32	0.06	<0.001**									
Aerobic fitness, *c2*	0.20	0.10	0.045									
Aerobic fitness × gender (girl), *i3*	0.09	0.10	0.335									
Muscular fitness → Cognitive function → Math performance												
Cognitive function test	-			-			-					
Muscular fitness, *a*										-0.14	0.10	0.148
Muscular fitness × gender (girl), *i1*										0.22	0.10	0.027
Arithmetic skills	-			-			-					
Cognitive function test, *b1*										0.35	0.06	<0.001**
Muscular fitness, *c1*										0.00	0.09	0.993
Muscular fitness × gender (girl), *i2*										0.15	0.09	0.097
Teacher-rated math	-			-			-					
Cognitive function test, *b2*										0.37	0.06	<0.001**
Muscular fitness, *c2*										0.12	0.09	0.171
Muscular fitness × gender (girl), *i3*										0.17	0.09	0.050
Motor skills → Cognitive function test → Math performance												
Cognitive function test							-					
Motor skills, *a*	-0.24	0.09	0.011	0.14	0.06	0.031				0.15	0.07	0.025
Motor skills × gender (girl), *i1*	0.21	0.09	0.024									
Arithmetic skills							-					

Cognitive function test, *b1*	0.34	0.06	<0.001**	0.36	0.06	<0.001**				0.35	0.06	<0.001**
Motor skills, *c1*	0.20	0.06	0.002*	0.13	0.07	0.055				0.13	0.06	0.022
Teacher-rated math							-					
Cognitive function test, *b2*	0.35	0.06	<0.001**	0.45	0.04	<0.001**				0.37	0.05	<0.001**
Motor skills, *c2*	0.26	0.06	<0.001**	0.17	0.06	0.004*				0.18	0.08	0.021

**p* < 0.01, ***p* < 0.001.

Note. All the models were adjusted for age, sex, pubertal stage, body fat percentage, mother's education and learning difficulties. The *a, b1, b2, c1, c2, i1, i2 and i3* are the paths in the model (see Figure 1).

Abbreviations: B = standardized regression coefficient; PA = physical activity; PAL= Paired Associates Learning; RVP, Rapid Visual Information Processing; SE = standard error; SWM = Spatial Working Memory.

Table 4. The indirect associations of physical activity/fitness/motor skills on math performance through a computer-assisted cognitive function test.

	Mediator variables											
		Flanker			PAL			SWM			RVP	
	b	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*
BOYS †												
Self-reported physical activity	- ‡			- ‡								
Arithmetic skills							0.10	0.04	0.016	0.23	0.10	0.021
Teacher-rated math							0.04	0.01	0.014	0.07	0.03	0.022
Muscular fitness												
Arithmetic skills	0.07	0.04	0.072				0.02	0.06	0.726	0.14	0.07	0.047
Teacher-rated math	0.01	0.01	0.113				0.01	0.02	0.725	0.04	0.02	0.043
Motor skills												
Arithmetic skills	0.09	0.04	0.023	0.07	0.03	0.046	0.19	0.06	<0.001**	0.13	0.06	0.023
Teacher-rated math	0.02	0.01	0.068	0.02	0.01	0.070	0.07	0.02	0.001*	0.04	0.02	0.023
GIRLS †												
Self-reported physical activity	- ‡			- ‡								
Arithmetic skills							0.10	0.04	0.016	-0.02	0.06	0.710
Teacher-rated math							0.04	0.01	0.014	-0.01	0.02	0.709
Muscular fitness				- ‡						- ‡		
Arithmetic skills	0.07	0.04	0.072				0.17	0.06	0.003*	0.14	0.07	0.047
Teacher-rated math	0.01	0.01	0.113				0.06	0.02	0.003*	0.04	0.02	0.043
Motor skills												
Arithmetic skills	0.09	0.04	0.023	0.07	0.03	0.046	0.19	0.06	<0.001**	0.13	0.06	0.023

*$p < 0.01$, **$p < 0.001$.

Note. All the models were adjusted for age, sex, pubertal stage, body fat percentage, mother's education and learning difficulties.

† The indirect effects were estimated as equal in the boys and girls whenever interaction terms were not needed.

‡ There were no significant association between physical activity/fitness and cognitive function based on the correlations/ linear regression models and therefore, no path modeling was conducted.

Abbreviations: *b* = unstandardized indirect effect; PAL = Paired Associates Learning; RVP = Rapid Visual Information Processing; *SE* = standard error; SWM = Spatial Working Memory

Table 5. The indirect associations of physical activity/fitness/motor skills on math performance through a pen and paper measured cognitive function test.

	Mediator variables											
	Similarities			Matrix reasoning			Coding			Spatial relations		
	b	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*
BOYS †												
Self-reported physical activity	- ‡									- ‡		
Arithmetic skills				0.13	0.06	0.036	0.1	0.06	0.058			
Teacher-rated math				0.06	0.03	0.043	0.03	0.02	0.066			
Aerobic fitness				- ‡			- ‡			- ‡		
Arithmetic skills	-0.23	0.12	0.052									
Teacher-rated math	-0.08	0.04	0.047									
Muscular fitness	- ‡			- ‡			- ‡					
Arithmetic skills										-0.11	0.08	0.161
Teacher-rated math										-0.04	0.03	0.158
Motor skills							- ‡					
Arithmetic skills	-0.17	0.07	0.020	0.11	0.05	0.042				0.12	0.06	0.056
Teacher-rated math	-0.06	0.02	0.017	0.04	0.02	0.038				0.04	0.02	0.030
GIRLS †												
Self-reported physical activity	- ‡									- ‡		
Arithmetic skills				0.03	0.06	0.591	0.04	0.05	0.457			
Teacher-rated math				0.01	0.02	0.595	0.01	0.01	0.464			
Aerobic fitness				- ‡			- ‡			- ‡		
Arithmetic skills	0.14	0.09	0.117									

Teacher-rated math	0.05	0.03	0.126									
Muscular fitness	-‡			-‡			-‡					
Arithmetic skills										0.11	0.07	0.117
Teacher-rated math										0.04	0.02	0.092
Motor skills							-‡			-‡		
Arithmetic skills	0.03	0.06	0.616	0.11	0.05	0.042						
Teacher-rated math	0.01	0.02	0.617	0.04	0.02	0.038						

*$p < 0.01$, **$p < 0.001$

Note. All the models were adjusted for age, sex, pubertal stage, body fat percentage, mother's education and learning difficulties.

† The indirect effects were estimated as equal in the boys and girls whenever interaction terms were not needed.

‡ There were no significant association between physical activity/fitness and cognitive function based on the correlations/ linear regression models and therefore, no path modeling was conducted.

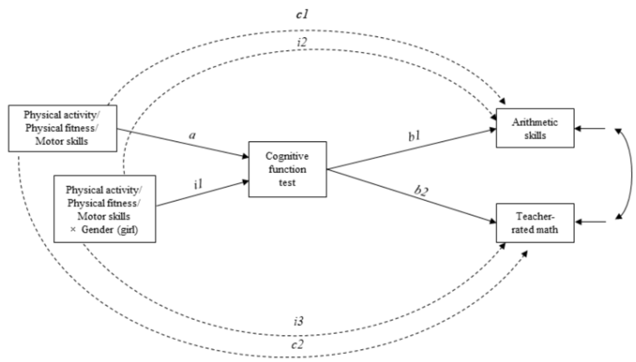
Abbreviations: *b* = unstandardized indirect effect; PAL = Paired Associates Learning; RVP = Rapid Visual Information Processing; *SE* = standard error; SWM = Spatial Working Memory

FIGURE LEGENDS

Figure 1. The path diagram of the mediator model linking physical activity/ physical fitness/ motor skills and math performance via cognitive outcomes. Dashed lines denote the associations which were estimated only when needed.

SUPPORTING INFORMATION

Supporting information is available.



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