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Importance of aerobic fitness and fundamental motor skills for academic achievement

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ABSTRACT

Objectives: Aerobic fitness and fundamental motor skills have both been related to children's academic achievement. Results of studies that have simultaneously related aerobic fitness and fundamental motor skills to academic achievement have provided inconsistent results, and the exact relations with achievement in distinct academic domains remain unknown. The current study examined unique relations between aerobic fitness, fundamental motor skills, and achievement in reading, mathematics and spelling.
Method: In total, 891 students (mean age = 9.17 years, *SD* = 0.66) from 22 primary schools participated. Two multilevel structural equation models were constructed, with relations between aerobic fitness (20m-shuttle run test), fundamental motor skills (tested with items of the Körperkoordinationstest für Kinder and Bruininks-Oseretsky Test for Motor Proficiency) and: (1) overall academic achievement, or; (2) achievement in the domains of reading, mathematics, and spelling (assessed with standardized academic achievement tests).
Results: Fundamental motor skills were more strongly related to overall academic achievement than aerobic fitness, but the exact relations differed by academic domain. Aerobic fitness predicted spelling achievement, whereas motor skills predicted reading achievement, and both were predictive of mathematics achievement.
Conclusions: Although more research is needed to disentangle the exact way in which aerobic fitness, motor skills, and academic achievement are linked, the results suggest that children's academic achievement benefits most from engagement in various physical activities which target both aerobic fitness and gross motor skills. These findings emphasize the importance of providing children with opportunities to engage in a wide variety of sports and activities.

1. Introduction

Engagement in regular physical activity is important for children to remain physically active throughout life (Janz, Dawson, & Mahoney, 2000), for their physical fitness and health (see Kohl & Cook, 2013), and for their development of motor skills (Riethmuller, Jones, & Okely, 2009). In recent years, research has also provided evidence for the beneficial effects of physical activity on children's academic performance in primary school (see for example de Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018; Donnelly et al., 2016; Vazou, Pesce, Lakes, & Smiley-Oyen, 2016). In line with the positive effects of physical activity on academic achievement, studies have shown that fitter children show better academic achievement than their less fit peers (de Bruijn, Hartman, Kostons, Visscher, & Bosker, 2018; Santana et al., 2017), and that children with better developed motor skills generally also perform better at school (Haapala, 2013).

1.1. Physical fitness and academic achievement

Most studies on relations between the physical and cognitive domain have focused on the association between cardiovascular aspects of physical fitness (also termed 'aerobic fitness') and academic achievement. Aerobic fitness refers to the ability to engage in physical activity for a protracted period of time (Caspersen, Powell, & Christenson, 1985). Strong evidence for a positive association between aerobic fitness and academic achievement in both children and adolescents has

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been provided, with higher levels of aerobic fitness being related to better academic performance (see Santana et al., 2017 for a systematic review). The most consistent relations between aerobic fitness and academic achievement are found in the domain of mathematics (Chaddock-Heyman et al., 2015; Chomitz et al., 2008; de Bruijn et al., 2018; Lambourne et al., 2013), although relations have been found for spelling (de Bruijn et al., 2018; Pindus et al., 2016) and reading (Chomitz et al., 2008) as well.

Aerobic fitness is argued to be related to cognitive performance via short- and long-term changes in brain regions responsible for learning and memory. In the short-term, cerebral blood flow increases (Etnier et al., 1997), and an upregulation of brain growth factors (e.g. brain-derived neurotrophic factor) and monoamines (dopamine, norepinephrine and epinephrine; Best, 2010) takes place. In the long-term these short-term effects result in the development of new blood vessels (angiogenesis) and neurons (neurogenesis), and an increase in synaptic plasticity in the brain areas that support various cognitive functions (Best, 2010). The positive adaptations of physical activity thus not only result in higher levels of fitness in the body, but also in the brain (Hillman, Erickson, & Kramer, 2008).

1.2. Fundamental motor skills and academic achievement

Besides studies examining the relations between aerobic fitness and academic achievement, there is research focusing on the relations between motor competency and academic achievement. In our study we use the term 'fundamental motor skills' to refer to children's motor competency. Fundamental motor skills are seen as the building blocks for the development of more complex and specialized movements and they are believed to be important predictors of a lifelong active lifestyle (e.g. Stodden et al., 2008). Fundamental motor skills are generally developed during childhood and include object-control skills (e.g. throwing and catching), locomotor skills (e.g. running and jumping), and stability skills (e.g. balancing and twisting; Gallahue, Ozmun, & Goodway, 2012).

Several explanations have been provided for the relation between cognitive and motor skills. Both sets of skills have common underlying processes such as monitoring, sequencing, and planning; both show an accelerated development between the ages of five and ten, and therefore are expected to develop similarly; and there are suggestions that motor and cognitive skills co-activate the same brain areas, namely the prefrontal cortex, the cerebellum, and the basal ganglia (see van der Fels et al., 2015).

Studies on the relation between fundamental motor skills and academic achievement have indicated that primary school children with better motor performance generally also perform better at school compared to children with lower motor performance (see Haapala, 2013 for a review) and that early fundamental motor skills are predictive of reading and mathematics achievement later on in school (Son & Meisels, 2006). In line with these findings, poorer fundamental motor performance has been related to larger learning deficits among children with learning disabilities (Vuijk, Hartman, Mombarg, Scherder, & Visscher, 2011; Westendorp, Hartman, Houwen, Smith, & Visscher, 2011) and many children who enter school with fundamental motor skill deficits also have problems with learning how to read and write later on (see Ericsson, 2008). Although research has indicated that motor skills and academic achievement are related, until now few studies have looked at the relations between motor skills and academic achievement in specific academic domains.

1.3. Aerobic fitness vs motor skills

Most studies that have examined the relations between aerobic fitness, motor skills, and academic achievement focused on only one aspect of the physical domain, that is: aerobic fitness OR motor skills. This is a limitation within previous research as it has been shown that aerobic fitness and motor skills are associated, in that fitter children often also have better developed motor skills (e.g. Lubans, Morgan, Cliff, Barnett, & Okely, 2010).

In one of the few studies that did examine relations between aerobic fitness, motor skills and academic achievement it was found that both aerobic fitness and motor skills were related to children's (aged 6–18 years) academic achievement in reading and mathematics, with stronger relations for motor ability than for cardiorespiratory capacity (standardized coefficients (β) for motor skills ranging from $\beta = 0.158$ to $\beta = 0.208$, and for aerobic fitness ranging from $\beta = 0.109$ to $\beta = 0.136$; Esteban-Cornejo et al., 2014). Studies by Haapala et al. (2014) and Aadland et al. (2017) found that the unique associations of aerobic fitness and motor skills with academic achievement in primary school differed for boys and girls. Still, despite these gender-specific associations Haapala et al. (2014) concluded that motor performance seems to be more important for academic skills than aerobic fitness.

Studies examining the relations of aerobic fitness and motor skills with other aspects of cognitive functioning (e.g. working memory and attention; Aadland et al., 2017) have also reported stronger relations between motor skills and cognition than between aerobic fitness and cognition. Although the terms 'cognitive functioning' and 'academic achievement' cannot be used interchangeably, as both refer to different concepts, cognitive functions are important predictors of academic performance (e.g. Best, Miller, & Naglieri, 2011; Diamond, 2013), making it likely that they relate to aerobic fitness and motor skills in the same way. It has been suggested that motor skill learning (compared to aerobic activities) more strongly relies on the brain structures and functions also involved in cognitive functioning, resulting in stronger relations between motor skills and cognitive performance than between aerobic fitness and cognition (Koutsandréou, Wegner, Niemann, & Budde, 2016; Voelcker-Rehage & Niemann, 2013). In line with this reasoning, a meta-analysis by De Greeff and colleagues (2018) showed that physical activity interventions focusing on cognitively-engaging physical activity targeting more complex (motor) skills had a moderate-to-large positive effect (ES = 0.53) on cognitive performance of children in primary school, compared to a small-to-moderate positive effect (ES = 0.29) for aerobic physical activity programs that aim to target aerobic fitness. In their review and meta-analysis, Vazou et al. (2016) reached the same conclusion on the effects of different types of physical activity on cognition in primary school.

1.4. Distinct academic domains

Besides the hypothesis that aerobic fitness and motor skills are expected to relate differently to academic achievement, it is likely that these relations will differ depending on which academic domain is examined. Mathematics, reading, and spelling are often seen as the core academic domains, because well-developed skills in these domains are critical for performance in other scholastic domains such as geography and history, and for success in children's further career (Onderwijsraad, 2011). The cognitive skills important for mathematics are not the same as those needed for reading and spelling (e.g. de Bruijn et al., 2018; St Clair-Thompson & Gathercole, 2006). Therefore the extent to which aerobic fitness and motor skills are predictive of performance in those domains will also differ. Some support has been provided for these specific relations, but results are not conclusive. For example, studies have reported positive relations of aerobic fitness with mathematics, but not with reading, whereas others have found the exact opposite (see Donnelly et al., 2016). Little is known about the specific relations between motor skills and academic achievement, but a review by van der Fels et al. (2015) has shown that the relations between motor skills and cognitive skills are also more specific rather than general. As academic achievement and cognitive functions such as attention and working memory are closely related (Best et al., 2011), it can be expected that the relation between motor skills and academic achievement will be specific instead of general as well.

Gaining more insight into the differential relations of aerobic fitness and motor skills with academic achievement is important as reading, mathematics, and spelling are skills that are essential for a child's development (OECD, 2016). Children need these academic skills to reach full potential, in turn paving the road to a successful professional life, and these skills are important for health and well-being (OECD, 2016). Finding out how aerobic fitness and motor skills are related to academic achievement may help in designing physical interventions to effectively target children's academic achievement simultaneously with their aerobic fitness and motor skills. Following the expectation of specific relations for the distinct academic domains, it is likely that these interventions should focus on different aspects of children's physical development, depending on the academic domain that one aims to be target.

1.5. Research aims

As results of the few studies that have examined simultaneous relations of aerobic fitness and motor skills with academic achievement are equivocal (Aadland et al., 2017; Esteban-Cornejo et al., 2014; Haapala et al., 2014), it seems important to examine these relations in a more sensitive way, by making a distinction between the different academic domains. Therefore, the present study aimed to examine the differential relations of aerobic fitness and motor skills with academic achievement in primary school. In addition, as previous studies mainly examined relations with overall academic achievement or achievement in very specific domains (e.g. numeracy), the present study aimed to examine *specific* relations between aerobic fitness, motor skills and academic achievement in different academic domains: reading, mathematics, and spelling.

Based on previous results in children in primary school (Aadland et al., 2017; Esteban-Cornejo et al., 2014; Haapala, 2013; Haapala et al., 2014; Vazou et al., 2016) the relation between motor skills and academic achievement was expected to be stronger than the relation between aerobic fitness and academic achievement. Relations were examined for the domains of reading, mathematics and spelling separately, although no specific hypotheses were formulated, because previous studies on relations between aerobic fitness, motor skills, and academic achievement have remained inconclusive (see Donnelly et al., 2016).

2. Methods

2.1. Participants

In total, 891 students (451 girls, 50.6%) from 22 primary schools (grades 3 and 4) in the Netherlands participated in this study. Mean age of the participating students was 9.17 years (SD = 0.66), with 51.2% (n = 456) drawn from Grade 3 and 48.8% (n = 435) from Grade 4. Students had a mean Body Mass Index (BMI) of 16.73 (SD = 2.41; based on n = 857, because of missing values for 34 (3.8%) students). Based on the classification values by Cole and Lobstein (2012), p. 724 students (81.3%) had a healthy weight, 109 (12.2%) were overweight, and 24 (2.7%) were obese. Informed consent was provided for all children by their legal guardians. The study was ethically approved by the ethics committee of the Faculty of Behavioral and Movement Sciences at the Vrije Universiteit Amsterdam.

2.2. Materials

2.2.1. Aerobic fitness

Shuttle run. The 20m Shuttle Run Test of the Eurofit physical fitness test battery (van Mechelen, van Lier, Hlobil, Crolla, & Kemper, 1991) was administered as a measure of cardiovascular endurance, which was used as indicator of aerobic fitness. In this test, children ran back and forth between two lines that were 20m apart within a specific time interval that was indicated by audio signals. The interval between each successive signal became smaller as the test proceeded. The test ended when a child failed to reach a line prior to the signal on two successive trials. The number of completed tracks (i.e. the number of times a child had run back and forth) was used as a score of aerobic endurance. The Shuttle Run Test is considered a reliable (test-retest reliability r = 0.89; Leger, Mercier, Gadoury, & Lambert, 1988) and valid measure of children's aerobic fitness (Leger et al., 1988; Voss & Sandercock, 2009), and is the most appropriate test of aerobic fitness in children and adolescents (Artego et al., 2011).

2.2.2. Fundamental motor skills

A score for proficiency in fundamental motor skills was established with one item of the Bruininks-Oseretsky Test for Motor Proficiency, Second Edition (BOT-II; Bruininks, 1978; Bruininks & Bruininks, 2005) and three subtests of the Körperkoordinationstest für Kinder (KTK; Kiphard & Schilling, 1974; 2007).

Eye-hand coordination (BOT-II). The upper-limb coordination subtest of the BOT-II was used to measure eye-hand coordination. This subtest consists of seven tasks, such as bouncing and catching a ball, and catching a tossed ball with both hands. A total score for eye-hand coordination was computed by summing the number of points on the seven tasks. For each task, a total number of five (for five tasks) or 7 (for two tasks) points could be reached, resulting in a maximum total score of 39 points. The BOT-II is a reliable (test-retest reliability is 0.80) and valid test for assessing motor proficiency in children (Deitz, Kartin, & Kopp, 2007).

Locomotor skills (KTK). Children's level of locomotor skill was established with two subtests of the KTK: shifting platforms and jumping laterally. In the shifting platforms test a child stood with both feet on a platform (25 cm × 25 cm) which was supported by four legs of 3.7 cm in height. The child was then asked to place a second identical platform alongside the first one using both hands. The child stepped on this second platform, replaced the first platform in the same manner and stepped upon this newly placed platform again. A child was awarded two points for each successful transfer from one platform to the next: one point for shifting the platform and one point for transferring the body. A total score was calculated by summing the number of points of two trials of 20s. Test-retest reliability of the shifting platforms subtest is 0.85 (Kiphard & Schilling, 1974; 2007).

In the jumping laterally test a child stood on a mat with a wooden slate in the middle and made consecutive jumps from side to side over the slate as quickly as possible. Each child got two attempts to make as many jumps as possible within 15 s. The total number of correct jumps in the two trials together was recorded as total score. Test-retest reliability of the jumping laterally subtest is good (α = 0.95; Kiphard & Schilling, 1974; 2007).

Balance (KTK). The balance subtest of the KTK was used to measure children's balancing skills. In the balance subtest a child walked backwards on three 3m long balance beams with decreasing widths of 6, 4.5 and 3 cm. For each balance beam a child got three attempts to make as many steps backwards (with a maximum of eight) as possible. The number of successful steps per attempt was recorded. Each attempt had a maximum score of eight steps leading to a maximum score of 24 steps per balance beam and a total maximum score of 72 for the three balance beams together. The balance subtest is a valid and reliable measure of children's balancing skill (test-retest reliability is 0.80; Kiphard & Schilling, 1974; 2007).

The KTK is a reliable (test-retest reliability α = 0.97) and valid measure of motor coordination in children of 5–15 years (Kiphard & Schilling, 1974; 2007). The KTK originally consisted of four subtests, but the fourth subtest (hopping for height) was not included in the present study due to time constraints. A previous study has demonstrated that this shorter version of the KTK shows substantial agreement with the original four subtest KTK (r = 0.97; Novak et al., 2017).

2.2.3. Academic achievement

Standardized tests. Academic achievement in reading, mathematics and spelling was measured with standardized achievement tests that are part of the Dutch child academic monitoring system (CAMS; Gillijns & Verhoeven, 1992).

In the reading test, children read several different types of texts (e.g. informative or argumentative) and answered 25 multiple choice questions pertaining to these texts, resulting in a maximum score of 25. The reading test provides a measure of reading comprehension, interpretation of written texts, looking up information and summarizing written texts. Reliability (test-retest reliability = .90) and validity of the reading test are good (Tomesen, Weekers, Hilte, Jolink, & Engelen, 2016).

The mathematics test consisted of 20 questions measuring general mathematics ability in the following domains: number sense, arithmetic, knowledge on fractions and ratios, geometry, time and money, and knowledge of charts and figures. Assignments included both basic arithmetic exercises as well as mathematical problems that had to be extracted by the child itself from the information provided in a short text. The mathematics test has demonstrated acceptable reliability (test-retest reliability > 0.90) and valid measure of children's mathematics ability (Hop, Janssen, & Engelen, 2016).

The spelling test consisted of a dictation in which the teacher read aloud a sentence and repeated one word out of that sentence, which children had to correctly write down. The test consisted of 25 words, resulting in a maximum score of 25. Reliability (test-retest reliability > 0.90) and content and construct validity of the spelling test are good (Tomesen, Wouda, & Horsels, 2016).

School-based measures. As additional indicators of academic achievement, ability scores in reading, mathematics and spelling were derived from the CAMS (Gillijns & Verhoeven, 1992) by the schools. The CAMS test battery is used by most Dutch primary schools to monitor progress in their student's academic skills throughout primary education. The CAMS tests for reading, mathematics and spelling are administered twice a year.

The reading test is a valid and reliable ($r = 0.85$) measure of reading comprehension (Feenstra, Kamphuis, Kleintjes, & Krom, 2010). The reading test measures reading comprehension, interpretation of written texts, looking up of information and summarization of written texts.

The mathematics test is a valid and reliable ($r = .91$ to .93) measure of students mathematical skills (Janssen, Verhelst, Engelen, & Scheltens, 2010). The test measures performance on different mathematical aspects, such as number sense and computation, geometry, and algebra.

The spelling test is a valid and reliable ($r = 0.88$ to 0.91) test consisting of two parts (De Wijs, Kamphuis, Kleintjes, & Tomesen, 2010). The first subtest is a dictation in which the teacher reads a sentence aloud and repeats one word out of that sentence. Children have to correctly write down this specific word. The second part is a multiple choice test in which children have to identify which word out of a list of words is spelled incorrectly.

Raw scores on these tests are converted to a standardized proficiency score and level. Five proficiency levels are used (I to V, I being the highest and V being the lowest level), each making up 20% of the students. These norm scores and levels can be used to keep track of a student's progress by comparing current performance to scores reached in previous years (Janssen & Hickendorff, 2008). The proficiency levels on the last test of the previous school year (end grade 2 for grade 3 students and end grade 3 for grade 4 students) were used as a second indicator of academic skill.

2.3. Procedure

All children were tested on the academic achievement tests and physical ability tests described above at their own school by trained research assistants. Children's motor skills and aerobic fitness were tested during two or three regular physical education lessons. Children completed the motor tests in a circuit form in which they went by all the test stations one by one in small groups. The 20m shuttle run test was administered classically in another lesson, approximately one week later.

2.4. Analyses

IBM SPSS Statistics 23.0 for Windows was used for missing value analyses. Missing data were observed on one or more variables for 193 of the participants. Little's MCAR test was not significant ($\chi^2(283) = 53.33$, $p = 1.00$), indicating that the data were missing completely at random. Full-information maximum likelihood (FIML) estimation was conducted in Mplus 7.31 (Muthén & Muthén, 1998–2006) to impute missing data by computing a likelihood function for each participant based on available data. FIML is a highly recommended approach to handle missing data (see Enders, 2010).

The academic achievement tests that were conducted in the classroom were grade-appropriate (i.e grade 3 made different tests than grade 4). Therefore, scores on all measures were converted into grade-specific standardized scores by standardizing them based on the mean and standard deviation of the participant's grade. The variables for the school-based academic achievement measures and for gender were not standardized, as the former are already converted based on grade, and the latter was kept as a dichotomous variable representing two categories.

To analyze the independent associations between aerobic fitness, motor skills, and academic achievement, structural equation (SEM) models were built in Mplus using weighted least squares means and variances adjusted (WLSMV) estimation. The root mean square error of approximation (RMSEA), comparative fit index (CFI), and Tucker-Lewis index (TLI) were used as fit indices, with cut-offs of 0.06, 0.90, and 0.90 respectively (Hu & Bentler, 1998). The conventional Chi-square statistic (χ^2) is reported as well, but was not used for assessing model fit as it is sensitive for model size, sample size, and distribution of variables (Hu & Bentler, 1998).

Aerobic fitness and fundamental motor skills were used as predictors of the outcome variables academic achievement in mathematics, reading and spelling. One single-indicator latent variable was constructed for aerobic fitness (as indicated by shuttle run test scores), with the corresponding factor loading fixed at 1 and indicator variance (e) fixed at the product of the measure's sample variance [VAR(x)] and $1 - \rho$, where ρ represents the reliability of the test (0.80, see above; Brown, 2006, p. 139). A latent factor was constructed to represent fundamental motor skills, made-up out of the four tests for motor skills: ball skills, jumping laterally, shifting platforms, and balance. Three latent variables were constructed for academic achievement, one for each domain, all made up out of the two academic achievement measures: the standardized tests and the school-based measures (CAMS-scores). Age, gender, and BMI were included as covariates and were related to aerobic fitness and motor skills, and the three academic achievement outcome measures. Age and gender were further related to BMI. Covariances between motor skills and aerobic fitness, and between the three academic domains were added, as relations between those variables were expected based on theoretical considerations. Standardized estimates of path coefficients (β-values) and corresponding p-values were obtained for significance testing.

3. Results

Mean scores on the tests for aerobic fitness, motor skills, and academic achievement are presented in Table 1. Correlations between included variables are presented in Table 2.

Table 1
Means, standard deviations and score range on the physical and academic achievement tests.

	Physical tests			
	N	*M*	*SD*	Range
Aerobic fitness				
20m SRT (n completed tracks)	839	35.3	15.5	5–85
Fundamental motor skills				
Ball skills (total points)	837	30.8	5.2	13–39
Jumping lat. (n jumps)	846	49.1	15.5	10–84
Shifting plat. (n relocations)	850	34.1	9.1	9–65
Balancing (n steps, total score)	854	40.6	13.6	4–72
	Academic achievement			
	N	*M*	*SD*	Range
Reading				
Stand. test (n correct)	852	18.3	4.8	3–25
CAMS level (I – V)	844	2.8	1.4	1–5
Mathematics				
Stand. test (n correct)	878	14.4	4.3	0–20
CAMS level (I – V)	843	2.7	1.4	1–5
Spelling				
Stand. test (n correct)	870	18.2	5.3	1–25
CAMS level (I – V)	847	2.8	1.5	1–5

Note. Jumping lat., jumping laterally; shifting plat., shifting platforms; SRT, Shuttle Run Test; stand., standardized; CAMS, Child Academic Monitoring System.

3.1. *Main analyses*

3.1.1. *Confirmatory factor analysis*

Before the relations in the structural model were examined, a confirmatory factor analysis was conducted to test whether the theoretical measurement model was a good representation of the data. The model with a single-indicator factor for aerobic fitness, a multi-indicator factor for motor skills, three multi-indicator factors for academic achievement, and added covariances between motor skills and aerobic fitness, and between the three academic domains proved to have an acceptable fit to the data ($\chi^2(35) = 65.11$, RMSEA = 0.03, CFI = 0.98, TLI = 0.98). Correlations between the latent variables in this model are presented in Table 3.

Table 3
Correlations between latent variables included in the SEM-models.

	1.	2.	3.	4.	5.
1. Reading	–				
2. Mathematics	.70 ***	–			
3. Spelling	.66 ***	.60 ***	–		
4. Fitness	.05	.27 ***	.08	–	
5. Motor skills	.10 *	.19 ***	.04	.58***	–

Note: * < 0.05 ** < 0.01 *** < 0.001

3.1.2. *Main analyses*

The measurement model tested above was consequently used to measure the relations in the structural model. First, aerobic fitness and motor skills were used as predictors of overall academic achievement, that is: one multi-indicator higher-order factor with the latent variables for reading, mathematics, and spelling as indicators. This model proved to fit the data acceptably ($\chi^2(63) = 237.09$, RMSEA = 0.06, CFI = 0.92, TLI = 0.89). Significant paths in the model are presented in Figure 1. (The full model including non-significant paths, factor loadings, error terms, and covariances can be found in Appendix A).

A significant 15.8% of the variance in academic achievement was explained by aerobic fitness and motor skills, controlling for age, gender and BMI ($p < .001$). Motor skills were significant predictors of academic achievement ($\beta = 0.14$, $p = .024$, 95% CI: 0.02 to 0.22) indicating that children with better developed motor skills also performed better at school. The relation between aerobic fitness and academic achievement was not significant ($\beta = 0.12$, $p = .057$, 95% CI: 0.003 to 0.23). The covariates age ($\beta = -0.34$, $p < .001$, 95% CI: 0.40 to -0.28) and gender ($\beta = 0.11$, $p = .029$, 95% CI: 0.01 to 0.18) were significantly related to academic achievement, showing that younger students (within a grade level) and girls had a higher academic performance compared to boys and older students. BMI was not significantly related to academic achievement ($\beta = -0.01$, $p = .84$, 95% CI: 0.08 to 0.05).

3.2. *Separate academic domains*

Next, academic achievement was separated into the three different domains, i.e. reading, mathematics, and spelling, to examine whether the relations between aerobic fitness and motor skills and academic achievement were specific for each domain. This model proved to have an acceptable fit to the data ($\chi^2(53) = 161.05$, RMSEA = 0.05,

Table 2
Bivariate correlations between manifest variables included in the SEM-models.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Academic achievement														
1. Reading stand. test	–													
2. Reading CAMS	-.59***	–												
3. Math. Stand. test	.48***	-.37***	–											
4. Math. CAMS	-.45***	.48***	-.68***	–										
5. Spelling stand. test	.46***	-.40***	.41***	-.39***	–									
6. Spelling CAMS	-.75***	.48***	-.41***	.48***	-.75***	–								
Fitness														
7. SRT	-.001	-.06	.17***	-.23***	.01	-.09*	–							
8. Ball skills	-.03	.03	.09**	-.09*	.05	-.04	.33***	–						
9. Jumping laterally	-.01	-.07	.08*	-.10**	-.02	-.05	.33***	.31***	–					
10. Shifting platforms	.06	-.08*	.09*	-.13***	-.04	-.02	.23***	.19***	.38***	–				
11. Balance	.08*	-.09*	.04	-.06	.04	-.02	.16***	.16***	.31***	.23***	–			
12. Gender	.18***	-.10**	-.11**	.15 ***	.15***	-.14***	-.34***	-.28***	-.07	-.05	.14***	–		
13. Age	-.18***	.20***	-.26***	.22***	-.20***	.21***	.01	.16***	.10**	.04	.01	-.10*	–	
14. BMI	-.07	.08*	-.10**	.12***	-.05	.09*	-.35***	-.05	-.17***	-.15***	-.23***	.09**	.15***	–

Note * < 0.05 ** < 0.01 *** < 0.001; all variables (except for gender) are standardized based on grade means and sd's; stand., standardized; CAMS, Child Academic Monitoring System; SRT, = Shuttle Run Test; BMI, Body Mass Index

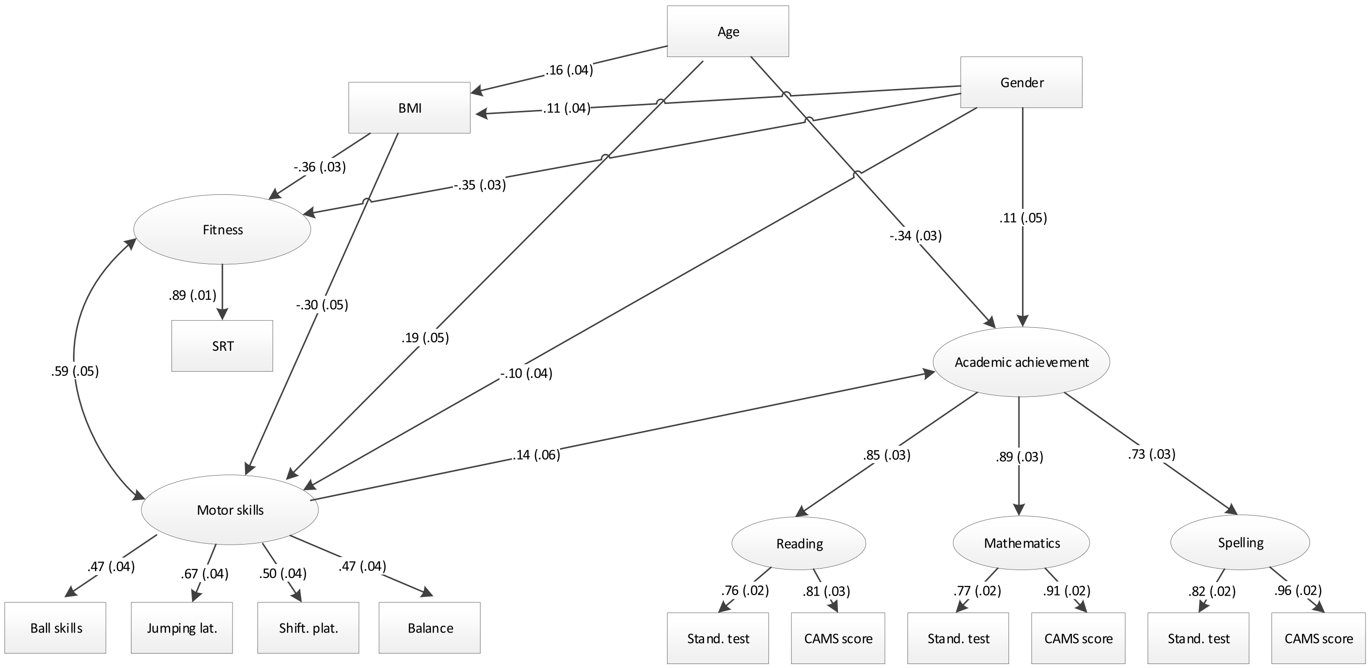

Fig. 1. Significant paths among aerobic fitness, motor skills, and overall academic achievement, controlling for gender, age, and BMI. Standardized path coefficients (betas) and associated standard errors are presented in the figure. Note: SRT, Shuttle Run Test; lat., laterally; shift. plat., shifting platforms; BMI, Body Mass Index; Stand., standardized; CAMS, Child Academic Monitoring System.

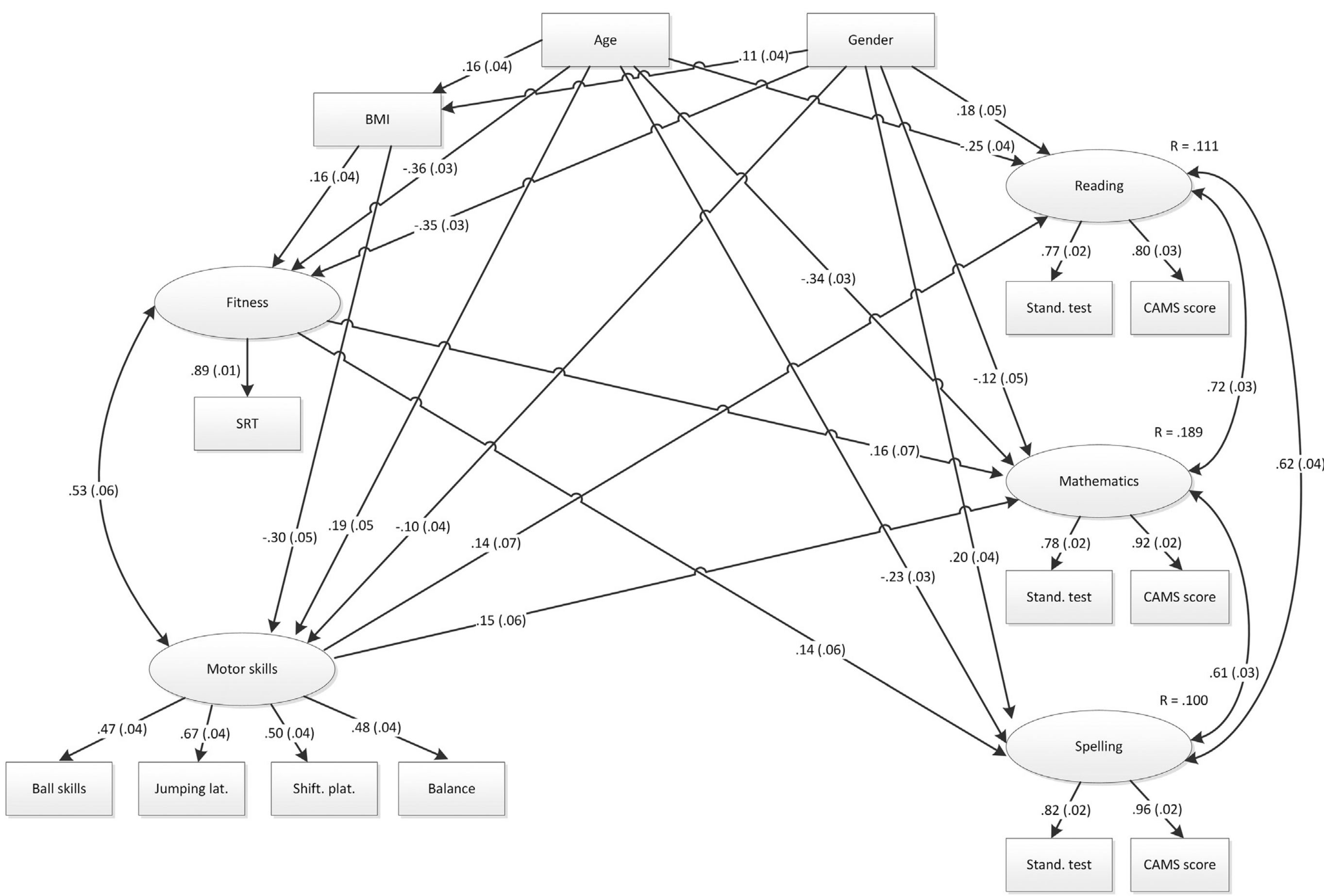

Fig. 2. Significant paths among aerobic fitness, motor skills, and academic achievement in reading, mathematics, and spelling, controlling for gender, age, and BMI. Standardized path coefficients (betas) and associated standard errors are presented in the figure. Note: BMI, Body Mass Index; SRT, Shuttle Run Test; lat., laterally; shift. plat., shifting platforms; Stand., standardized; CAMS, Child Academic Monitoring System.

CFI = 0.95, TLI = 0.92). Significant relations in the model are presented in Figure 2. The χ^2-difference test indicated that this second model including the three academic domains separately had a better fit than the first model where academic achievement was represented as one overall factor (χ^2-difference (10) = 95.93, $p < .001$).

3.2.1. Reading

A significant 11.1% ($p < .001$) of the variance in reading performance was explained by the relation with motor skills (β = 0.14, $p = .04$, 95% CI: 0.01 to 0.25), controlling for age, gender and BMI. Children with better developed motor skills were more likely to perform better in reading as well, compared to their peers with less well-developed motor skills. Aerobic fitness was not a significant predictor of achievement in reading (β = 0.03, $p = .66$, 95% CI: 0.10 to 0.13). The covariates gender (β = 0.18, $p < .001$, 95% CI: 0.10 to 0.26) and age (β = −0.34, $p < .001$, 95% CI: 0.35 to −0.18) were significantly related to reading achievement, indicating that girls and younger students (within a grade level) had better reading performance than boys and older students. BMI was not significantly related to reading achievement (β = −0.03, $p = .41$, 95% CI: 0.10 to 0.03).

3.2.2. Mathematics

A significant 18.9% ($p < .001$) of the variance in mathematics performance was explained by the relationship between aerobic fitness (β = 0.16, $p = .017$, 95% CI: 0.03 to 0.27) and motor skills (β = 0.14, $p = .021$, 95% CI: 0.02 to 0.25), controlling for age, gender and BMI ($p < .001$). Students with better developed motor skills and higher levels of aerobic fitness also performed better in the domain of mathematics. Wald test showed that the path coefficients of aerobic fitness and motor skills did not significantly differ (χ^2 (1) = 0.66, $p = .42$), indicating that aerobic fitness and motor skills were equally strong predictors of mathematics achievement. The covariates gender (β = −0.12, $p = .01$, 95% CI: 0.21 to −0.03) and age (β = −0.34, $p < .001$, 95% CI: 0.41 to −0.27) were significantly related to mathematics performance, indicating that boys and younger students (within a grade level) performed better in mathematics. BMI was not significantly related to mathematic achievement (β = 0.02, $p = .58$, 95% CI: 0.06 to 0.10).

3.2.3. Spelling

A significant 10.0% ($p < .001$) of the variance in spelling performance was explained by the relation with aerobic fitness (β = 0.14, $p = .04$, 95% CI: 0.01 to 0.25), controlling for age, gender, and BMI, showing that children who had higher levels of aerobic fitness also performed better in spelling. Motor skills was not a significant predictor of spelling achievement (β = 0.019, $p = .75$, 95% CI: 0.10 to 0.11). The covariates gender (β = 0.20, $p < .001$, 95% CI: 0.11 to 0.29) and age (β = −0.23, $p < .001$, 95% CI: 0.29 to −0.16) were significantly related to spelling achievement, with girls and younger students (within a grade level) performing better in spelling. BMI was not significantly related to spelling achievement (β = −0.01, $p = .82$, 95% CI: 0.08 to 0.06).

4. Discussion

In the present study, it was found that fundamental motor skills were stronger predictors of academic achievement than aerobic fitness. This conclusion needs to be nuanced however, as the relations between aerobic fitness and fundamental motor skills, and academic achievement depended on the academic domain involved. In reading, only fundamental motor skills were a significant predictor of achievement, whereas in spelling only aerobic fitness was a predictor of achievement. In mathematics both fundamental motor skills and aerobic fitness predicted achievement.

Our results are in line with studies reporting stronger relations between motor skills and other cognitive functions (such as working memory) in children with a similar age, compared to the relations between aerobic fitness and cognition (Aadland et al., 2017; Haapala et al., 2014). As previous studies mainly focused on the relations of aerobic fitness and motor skills with cognitive functions such as working memory, or between academic achievement and either physical fitness or motor skills, our study is one of the first to report that motor skills, compared to aerobic fitness, are more strongly related to academic achievement in a large sample of typically developing children.

4.1. Specific relations

However, the conclusions do not seem to be that straightforward, as we found specific relations between aerobic fitness and fundamental motor skills, and academic achievement in the different academic domains. For aerobic fitness, previous studies have also reported different relations with academic achievement depending on the academic domain involved (see Donnelly et al., 2016 for a systematic review). We continue on these results by finding relations between aerobic fitness and performance in mathematics and spelling, but not in reading. For fundamental motor skills, few studies have focused on the specific relations with academic achievement. Still, as differential relations between categories of cognition and motor skills have been reported in pre-pubertal children (< 13 years; van der Fels et al., 2015), different relations between fundamental motor skills and academic achievement in specific domains were expected in our study as well. Indeed, our results supported this hypothesis by finding relations between fundamental motor skills and performance in reading and mathematics, but not in spelling.

The development of aerobic fitness and motor skills is closely related to engagement in physical activity and it is probable that the relations of academic performance with aerobic fitness and motor skills are brought about via engagement in physical activity (see Haapala, 2013). Following this line of reasoning, results of the present study, although cross-sectional, suggest that children's academic achievement could benefit from engagement in physical activity. Physical activity programs focusing on the development of motor skills could be more effective than aerobic physical activity programs, although the effectiveness of these type of programs can be expected to differ depending on the specific academic domain involved. As results of the present study are cross-sectional, further research is needed to provide support for this hypothesis.

4.2. Explanatory mechanisms

The different mechanisms that are brought forward to explain the relations between cognition and either aerobic fitness or fundamental motor skills assume that aerobic fitness and motor skills are associated with cognition and academic achievement via different routes in the brain (Haapala, 2013; Voelcker-Rehage & Niemann, 2013). This assumption leads us to hypothesize that motor skills are more strongly linked to brain areas and networks involved in reading comprehension, whereas aerobic fitness mainly relates to neural networks and regions involved in spelling. In support of this suggestion, previous studies in typically developing 9- and-10-year olds have related aerobic fitness to increased volume of the hippocampus (Chaddock et al., 2010), which is critical for fact retrieval, an important skill in spelling. The exact brain structures and functions that are related to motor skills remain unclear (Sigmundsson, Englund, & Haga, 2017). Some studies have suggested that motor skill learning relies more strongly on brain areas involved in the motor system (pre- and primary motor cortex, supplementary motor area, cerebellum, etc.) than the endurance-related capacities of aerobic fitness (Koutsandréou et al., 2016; Voelcker-Rehage & Niemann, 2013). Some of these motor areas have been implicated as important for reading development as well (Fulbright et al., 1999; Houdé, Rossi, Lubin, & Joliot, 2010), in line with our finding of a significant relation between motor skills and reading achievement. As the mechanisms underlying the specific relations were not examined in this study, more research is needed to disentangle the exact ways in which aerobic fitness, motor skills and the different academic skills are linked, and whether specific brain structures and functions can explain these relations (Cameron, Cottone, Murrah, & Girssmer, 2016).

Although we expect that these explanations can (at least partly) explain the found relations, it should be noted that there might also be different mechanisms at play. Psychosocial variables such as a child's social environment, self-esteem, mood, or school adjustment might also be involved (e.g. Bailey, 2016), as they are related to both aerobic fitness and motor skills as well as academic achievement. For future research it would be interesting to examine the role that these psychosocial variables play in explaining the relations between physical fitness, motor skills and academic achievement.

Relatedly, it should be considered that genetic factors may play a role as well. Genes are strongly related to both the development of physical fitness and motor skills, and academic performance (see Haapala, 2013). It is unclear to which extent genetic factors are the common cause of physical fitness, motor skills and academic achievement, but children's genetic background might at least partly explain the relations that were found in the present study.

4.3. Strengths and limitations

A strength of this study is the large sample size, which made it possible to construct well-fitting SEM models. In addition, the construction of SEM models in which various measures were used as indicators of academic achievement and motor skills resulted in reliable estimations of children's motor and academic skills, and the relations between these latent constructs. This advanced analysis enhances the reliability of the results that were found, by taking into account the multilevel structure of the data, by adequate handling of missing data, and by providing reliable estimations of the measured constructs.

Although the use of SEM can be seen as a strength, there are also some limitations in using this type of analysis (Tomarken & Waller, 2005). When constructing SEM models, it is easy to adapt the model to the data, resulting in a well-fitting factor structure which could have occurred at random or as a result of trial and error. A well-fitting model can easily lead to the assumption that: a) the model is a good representation of reality, and b) that all necessary and important variables are included, especially when using standardized test batteries such as those in the present study, it therefore seems vital to determine the operationalization of constructs beforehand, by following the theory provided by the included test batteries. Also, theory should be leading when deciding which variables should be included in SEM models. Although we based the factor structure of our models on theoretical assumptions, it could still be that the models presented here are not a good representation of real-world associations, despite providing an excellent fit to the data. These are important issues to keep in mind when using and interpreting this type of analysis.

This study also has some other limitations. Firstly, the study used cross-sectional data, which makes it impossible to make statements about causality. Secondly, only one aspect of physical fitness was examined, namely aerobic fitness. Physical fitness is, however, a multifacetted concept, also consisting of other components such as muscular strength and muscular endurance (Caspersen et al., 1985). Future research should examine other components of physical fitness as well. Lastly, it should be noted that the 20-m shuttle run test does not provide a true measure of aerobic fitness, as performance on the 20-m shuttle run test can be influenced by: other physical factors, such as motor coordination and adiposity; and by psychological factor such as motivation (Armstrong, 2017). The use of another instrument to measure aerobic capacity could have led to different results. Future studies should also include other measures of aerobic fitness to get a more reliable measure of 'true' aerobic capacity.

5. Conclusion and implications

In the present study it was found that fundamental motor skills were stronger predictors of overall academic achievement than aerobic fitness. When these relations were examined separately for the domains of reading, mathematics and spelling, the predicting value of aerobic fitness and fundamental motor skills was found to differ for the distinct academic domains. Aerobic fitness and fundamental motor skills are interrelated aspects of children's physical development however, as children with a higher level of aerobic fitness in general also have better developed motor skills and vice versa (e.g. Lubans et al., 2010). Although aerobic fitness and fundamental motor skills seem to be related to different aspects of academic achievement, as shown in the present study, *both* have been related to children's academic performance, emphasizing the importance of providing children with opportunities to engage in a wide variety of sports and activities to develop motor skills and improve aerobic fitness. These activities will probably be beneficial for children's physical, as well as their academic development.

Potential conflicts of interest

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

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Appendix A. Supplementary data

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