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Executive functions, visual-motor coordination, physical fitness and academic achievement: Longitudinal relations in typically developing children

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A B S T R A C T

The present longitudinal study included different school readiness factors measured in kindergarten with the aim to predict later academic achievement in second grade. Based on data of N = 134 children, the predictive power of executive functions, visual-motor coordination and physical fitness on later academic achievement was estimated using a latent variable approach. By entering all three predictors simultaneously into the model to predict later academic achievement, significant effects of executive functions and visual-motor coordination on later academic achievement were found. The influence of physical fitness was found to be substantial but indirect via executive functions. The cognitive stimulation hypothesis as well as the automaticity hypothesis are discussed as an explanation for the reported relations.

1. Introduction

A major challenge in children's life is a successful transition from kindergarten to school. While some children manage this important transition easily, others face problems when trying to adapt to their novel school environment. In this context, researchers aim to identify and quantify so-called "school readiness factors", child characteristics that predict later academic achievement in kindergarten children. While traditionally, domain-specific precursors for writing, reading, and mathematics, such as phonological awareness and number sense, were in the focus of school readiness research, a broader conceptualization of school readiness is now discussed (Pianta, Cox, & Snow, 2007). From this perspective, different domain-general characteristics of the child contribute substantially to the prediction of early academic achievement and school adjustment. Especially higher order self-regulatory abilities, particularly executive functions, have repeatedly and consistently been documented as being an important indicator of school readiness (for a recent review see Blair & Raver, 2015). Apart from a strong focus on executive functions, other domain-general child characteristics have engaged researchers' interest: among other, fine motor skills and physical fitness (e.g., Cameron et al., 2012; Schmidt et al., 2017), which are interrelated with each other (e.g., Oberer, Gashaj, & Roebers, 2017). In the present approach, therefore, these three domain-general factors of kindergarteners' school readiness were included to longitudinally estimate their *relative* predictive power for academic performance in children's second school year. The literature on these three concepts will be discussed in the following paragraphs.

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1.1. Executive functions

As mentioned above, executive functions are an important school readiness factor and their importance for academic achievement is consistently being reported (e.g., Blair & Raver, 2015). According to Miyake et al. (2000), executive functions is an umbrella term unifying at least three distinguishable, yet interrelated cognitive functions: inhibition, shifting and updating. Inhibition refers to the ability to suppress automatic or pre-potent impulses or responses; shifting is defined as the ability to flexibly shift between mental sets, multiple tasks or rules; and updating is the ability sustain, update or manipulate a limited amount of information in working memory (Diamond, 2013).

1.2. Visual-motor coordination

Visual-motor coordination as well as visual-spatial integration are both considered to belong to the broader term of fine motor skills. Fine motor skills thereby refer to the coordination of small muscle movements. More precisely, fine motor performance is based on visual perception and motor coordination, with the need to integrate these two aspects (Cameron, Murrah, Cottone, & Grissmer, 2016; Carlson, Rowe, & Curby, 2013; Sorter & Kulp, 2003). Under the term visual-spatial *integration* and with tests like the copy design test, these skills have been found to be related to writing and “penmanship” in more general terms and to predict academic achievement longitudinally (Cameron et al., 2012; Carlson et al., 2013; Cornhill & Case-Smith, 1996; Feder & Majnemer, 2007; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Pitchford, Papini, Outhwaite, & Gulliford, 2016). Much less work has addressed visual-manual *coordination*, typically assessed with tasks of manual dexterity (Henderson, Sugden, & Barnett, 2007). Visual-motor coordination comprises the control of small finger movements without the strong focus on integrating visual information, too. Two existing studies on visual-motor coordination suggest a link to achievement, either directly (Pitchford et al., 2016) or indirectly (Kim, Duran, Cameron, & Grissmer, 2017), while another did not (Carlson et al., 2013). Thus, since the link between visual-motor integration and academic achievement has been established while the link between visual-motor coordination has not, the focus of the present approach was laid on visual-motor coordination.

1.3. Physical fitness

Physical fitness is another factor indicative of school readiness that has only very recently received research attention (e.g., Chomitz et al., 2009; Fedewa & Ahn, 2011; Lopes, Santos, Pereira, & Lopes, 2013; van der Niet, Hartman, Smith, & Visscher, 2014). This lack of evidence is surprising since physical fitness is a popular construct and is often targeted in intervention programs; uncovering the impact of physical fitness for outcomes beyond health related measures may help to establish fitness programs even for children (Fedewa & Ahn, 2011; Ortega, Ruiz, Castillo, & Sjöström, 2008; Vandongen et al., 1995). Physical fitness is commonly understood to be a multidimensional construct consisting of different components involved in the performance of physical activities like aerobic endurance, muscle strength or agility (Bös, 1987; Ortega et al., 2008). Although the relation between physical fitness and academic achievement is far from being fully understood, positive relations to academic achievement in school-aged children were reported for aerobic endurance cross-sectionally (Castelli, Hillman, Buck, & Erwin, 2007; Chomitz et al., 2009; Welk et al., 2010) and longitudinally (Sardinha et al., 2016), as well as cross-sectionally for muscle strength (Castelli et al., 2007; Eveland-Sayers, Farley, Fuller, Morgan, & Caputo, 2009). In addition, agility was reported to be important and predictive for academic achievement in school-aged children (Kurdek & Sinclair, 2001; Lopes et al., 2013). Taken together, the link between physical fitness and academic achievement is frequently reported. Especially aerobic endurance seems to be consistently linked to academic achievement. However, these studies may have overestimated the impact of physical fitness on academic achievement as other important factors have not been included in those studies. Simultaneously addressing the influence of these different child characteristics will allow to estimate their relative contribution, an important next step for research in this domain.

In this context, another important question remains unanswered: *how* are visual-motor coordination and physical fitness linked to academic achievement? In other words, the underlying mechanisms driving this link have only rarely been targeted. The most prominent theoretical explanation for the link between physical fitness and academic achievement is the cardiovascular fitness hypothesis suggesting that physical activity causes functional and structural changes in the brain (Khan & Hillman, 2014; North, McCullagh, & Tran, 1990). In fact, magnetic resonance imaging studies revealed that especially the brain regions that are important for learning, such as the hippocampus, are affected through physical activity (Chaddock-Heyman et al., 2016). Event-related brain potential studies suggest that fitter children show a more efficient allocation of attentional resources (Hillman, Kamijo, & Scudder, 2011) and fitter children were also reported to be more physically active, than physically less active children (Ruiz et al., 2006). Consequently, the physical fitness hypothesis is one explanation for the reported links between physical fitness and academic achievement.

Another theoretical explanation that has recently been attracting more attention is the cognitive stimulation hypothesis. It assumes that coordinative demanding physical activity (for example, learning new sports or coordinative skills) not only increases physical fitness, but also enhances higher-order cognitive control processes, namely, executive functions (Best, 2010; Moreau, Morrison, & Conway, 2015; Tomporowski, Davis, Miller, & Naglieri, 2008). Assuming that physically fitter children engage in more physical activity (see above; Ruiz et al., 2006), it is conceivable that those children not only exercise and improve their fitness, but that by these means they have also more opportunities for motor skill learning. Learning new motor skills can be coordinatively as well as cognitively demanding and seems to be one way to improve cognitive functions, especially executive functions (Moreau et al., 2015; Pesce et al., 2013; Schmidt, Jäger, Egger, Roebers, & Conzelmann, 2015). Since executive functions are known to be a strong predictor of academic achievement (see above; Best, Miller, & Naglieri, 2011; Blair & Raver, 2015; Bull & Scerif, 2001; Willoughby, Blair, Wirth, & Greenberg, 2012), an indirect influence of physical fitness on academic achievement, via executive functions, can be expected. This was tested with the present approach.

It seems plausible to consider the relation between visual-motor coordination and academic achievement being of similar character: Exercising or learning new visual-motor coordination skills not only affects visual-motor performance, but also positively influences executive functions. This view is theoretically rooted in Piaget's theory of cognitive development (Piaget & Inhelder, 1966), as it assumes cognitive and motor development to be interdependent: developing motor skills enable the child to move and explore the environment which, in turn, promotes cognitive development. Likewise, cognitive abilities are needed to cope with complex motor requirements (Singer, 1981). Thus, a reciprocal influence of motor and cognitive development has been hypothesized. Empirically, cross-sectional correlations between visual-motor coordination and cognitive abilities (in particular executive functions) have been reported in children aged 4–11 years (Davis, Pitchford, & Limback, 2011; Oberer et al., 2017; Roebers & Kauer, 2009; Wassenberg et al., 2005). Further support stems from neuropsychological studies reporting that the same brain areas are activated during motor and executive function tasks (Diamond, 2000). Hence, executive functions are also a possible mediator for the link between visual-motor coordination and academic achievement. At the same time, in a typical school setting, children with better visual-motor coordination will have fewer difficulties to use or control the movement of pens compared to children with worse visual-motor coordination especially in the early school years when writing is not yet automatized (Cameron et al., 2016). Thus, beside the expected indirect effects (via executive functions), direct effects from visual-motor coordination to academic achievement should be taken into consideration.

1.4. The present study

To summarize, in addition to direct effects of executive functions, physical fitness, and visual-motor coordination on academic achievement, executive functions are a potential mediator, suggesting that indirect effects of physical activity and visual-motor coordination via executive functions exist. Only three studies have so far tested such indirect links empirically. In one cross-sectional study by van der Niet et al. (2014) using a latent variable approach and including 7- to 12-year old children, physical fitness was found to be significantly related to academic achievement ($\beta = .33$) and also to executive functions ($\beta = .43$). When executive functions were included into the model as a mediator, the direct link from physical fitness to academic achievement was negligible, while the indirect effect of physical fitness on academic achievement ($\beta = .41$) was stronger than the total effect ($\beta = .33$) and the direct effect, indicating a full mediation. Due to the cross-sectional design of the study, unfortunately, no long-term prediction and no causal conclusions can be made, leaving it yet open whether these results can be replicated in a longitudinal design. Similarly, Schmidt et al. (2017) tested the mediational role of executive functions in the relation between physical fitness and academic achievement in 10- to 12-year old children. They confirmed the significant indirect effect via executive functions using a short-term longitudinal design over a 10 week period. When the indirect path for endurance, strength, and agility were tested separately, the mediation by executive functions was confirmed only for agility. Another recent longitudinal study by Roebers et al. (2014) estimated a structural equation model with fine motor skills (visual-motor coordination) and non-verbal intelligence of kindergarten children being used as predictors of later academic achievement, indexed by mathematics, reading and spelling. The latent variable fine motor skills (visual-motor coordination), indexed by the subtests of the manual dexterity scale within the Movement Assessment Battery for Children 2 (M-ABC-2; Henderson et al., 2007) was found to be a long-term predictor for later achievement ($\beta = .42$), as was intelligence ($\beta = .30$). Importantly, when executive functions, indexed by shifting, inhibition and updating, were additionally included into the model, executive functions remained the only significant predictor ($\beta = .53$) for later academic achievement (fine motor skills (visual-motor coordination): $\beta = .17$; intelligence: $\beta = .15$; both n.s.). The results were identical when predicting academic outcomes over a one- and a two-year interval. Executive functions were the only significant predictor for later academic achievement and a significant correlation between fine motor skills (visual-motor coordination) and executive functions was reported in 5- to 6-year-olds ($\beta = .60$). These results support the assumption of a mediating role of executive functions in the relationship between fine motor skills (visual-motor coordination) and academic achievement, albeit no mediational models were tested. Further evidence stems from a similar study including adolescents, in which one specific subdomain of executive functions (working memory) had a mediational role for the relation between general motor coordination (assessed with the M-ABC-2) and general academic achievement (Rigoli, Piek, & Kane, 2012).

To summarize the reviewed literature, there are several studies separately addressing either the relations between physical fitness and academic achievement or between visual-motor coordination and academic achievement, respectively. Despite the aforementioned interrelatedness of these constructs with executive functions, only few studies additionally considered executive functions. In fact, to our knowledge, no study simultaneously included physical fitness, visual-motor coordination and executive functions for the prediction of later academic achievement. In the present longitudinal study, structural equation modelling is used and a model including all three constructs for the prediction of later academic achievement is provided. To estimate the relations on the level of the theoretical constructs, a latent variable approach is used. Hereby, the links are estimated on the basis of shared variances of the constructs. Based on the literature, we expect executive functions to be the strongest predictor of later academic achievement. Whether visual-motor coordination and physical fitness remain significant predictors when the effect of executive functions is controlled for, will be tested. With respect to the possible mediational role of executive functions, the indirect influence of visual-motor coordination and physical fitness via executive functions on academic achievement will also be estimated. By these means, a better understanding of the interrelations in young children will be achieved. This is of theoretical importance and of practical relevance, especially with respect to designing optimized interventions for enhancing school readiness in kindergarten children.

2. Method

2.1. Overview

A large sample of children completed different physical fitness and executive function tasks in kindergarten. 18 months later, i.e., when they were in second grade, the same tasks were completed again. Additionally, early academic achievement was assessed (reading and mathematics). The Ethics Committee of the Faculty of Human Sciences of the University of Bern, Switzerland (Approval No. 2013-12-733209) approved the study and children's participation was confirmed by their parent's written consent.

2.2. Sample

We tested 162 children from 13 different kindergartens in the vicinity of a European University town. The definitive sample consisted of $N = 134$ children (68 girls and 66 boys); 28 children were excluded because of missing data at the second measurement point. These children either moved away, had to repeat a class, were sick at the time of data collection or their new teacher decided not to participate in the follow-up measurement. At the first measurement point, the children were 5–7 years old ($M = 6.42$ years, $SD = 0.32$). Familial income per month, the subjective satisfaction with the income and the educational level of the parents were assessed, z-standardized and added up to a sum score for SES (*range* = −4.85–3.03; Alsaker, Nägele, Valkanover, & Hauser, 2008; Schick et al., 2006). German was not the first language of all children; those children with another first language were bilingual and their German skills were very good (they attended regular kindergarten and understood the instructions well). It is also worth mentioning that all children had the same amount of prior preschool experience.

2.3. Procedure

Testing took place during the morning hours. While group measurement was used for the academic achievement tests as well as for the fitness and motor tasks, executive functions were assessed individually. One session lasted 30–40 min and every child participated in only one session per day. For the computer-based tasks, we used the e-prime software (Psychology Software Tools, Pittsburgh, PA) and a laptop.

2.4. Materials

2.4.1. Executive functions

At both measurement points, we used the same three tasks to assess the common three distinct, yet related domains of executive functions; inhibition, shifting and updating (Miyake et al., 2000). Children completed an adapted version of the Flanker task (Eriksen & Eriksen, 1974) to assess inhibition and shifting, and a verbal updating task was used to assess the updating component. The internal consistency for these executive function measures was $\alpha = .57$ at the first measurement point.

In the Flanker task, the children had to feed a fish by pressing a button; either on the left or on the right side, depending on the fish's orientation. To assess inhibition, we used the standard block, in which five red fish are presented in a row. The child had to "feed" the central target fish (while ignoring the orientation of the flanking fish). They were to press the left external response button when the mouth of the central fish was facing to the left, and the right response button when the mouth was facing to the right, respectively. Children were instructed to respond as fast and accurate as possible. The children completed six practice trials, followed by 48 experimental trials; thereof, two thirds were incongruent: the central fish and flanking fish had an opposite orientation. Stimulus duration was set to max. 3500 ms and the interstimuli intervals varied randomly between 800 and 1400 ms. The z-transformed accuracy scores of the incongruent trials (percentage of correct responses) was used as dependent variable for inhibition (Gashaj, Uehlinger, & Roebers, 2016).

Two further blocks were added to assess shifting. First, the reversed block was added to introduce a new rule. In this block, the fish's color was changed to yellow and the children were instructed to "feed" the outer fish, which all had the same orientation (thereby ignoring the orientation of the central fish). Similar to the inhibition task, six practice trials preceded the 16 experimental trials, half of which were congruent and half of which were incongruent. Interstimulus interval and stimulus duration were identical to the standard block. In the following, final mixed block, both red and yellow fish were presented. Now, children had to flexibly switch between the two rules. After eight practice trials, 40 experimental trials followed (1/2 congruent; 1/2 incongruent, 20 with red and 20 with yellow fish). The maximum stimulus duration was set at 7000 ms. Again, we assessed accuracy of responses in the mixed trials. The z-standardized accuracy of the incongruent trials served as dependent variable for shifting (Gashaj et al., 2016).

To assess updating, we used the Backward Color Recall task (Schmid, Zoelch, & Roebers, 2008; Zoelch, Seitz, & Schumann-Hengsteler, 2005). In this verbal updating task, a sequence of differently colored discs was presented on the computer screen and children were instructed to recall them verbally in reversed order. After three practice trials, we started with a sequence of two discs. Whenever at least three out of six trials were recalled correctly, the sequence length was increased by one disc. We only used monosyllabic colors and we checked beforehand that the child wasn't color-blind. The inter-stimulus interval was set at 5000 ms with a presentation duration of one second per disc. The dependent variable for this task was the total number of correctly solved trials.

2.4.2. Visual-Motor coordination

Three visual-motor coordination tasks were used: Drawing Trail, Posting Coins and Threading Beads. The tasks derived from the

Movement Assessment Battery for Children (M-ABC-2; Petermann, 2009), and were administered according to the test manual. For the drawing trail, children had to draw a line between two preprinted lines as accurately as possible and the number of errors was used as dependent variable. For the posting coins task, children had to post plastic coins one by one into a box, once with the left and once with the right hand. For the threading beads task, children had to thread beads on a lace. Children were instructed to perform these two tasks as fast as possible and times to task completion were used as dependent variables. The dependent variables of the visual-motor coordination tasks were z-transformed and inverted if needed (so that higher scores always mirror better performance). Then, the z-scores were used as dependent variables. The internal consistency of the three visual-motor coordination tasks was $\alpha = .65$.

2.4.3. Physical fitness

Three tasks were used to assess physical fitness. The six-minute-run is known to measure aerobic endurance (Bös, 2001). For this task, children had to run as many meters as possible within six minutes on a circuit of 54 m. The distance run in meters was used as dependent variable. The standing long jump task is a strength task (Adam, Klissouras, Ravazzolo, Renson, & Tuxworth, 1993), and children had to jump as far as possible. They had to use both feet and the wider jump out of two trials, measured in centimeters, served as dependent variable. The jumping sideways task, used to measure agility, derives from the “Körperkoordinationstest für Kinder” (KTK; Kiphard & Schilling, 2000), and was administered according to the test manual. Children had to perform as many jumps as possible within 15 s by jumping from one side to the other on a small pad using both feet. The total number of correct sideway jumps out of two trials was used as dependent variable. All three dependent variables for physical fitness were z-transformed. The internal consistency of these physical fitness tasks was $\alpha = .56$

2.4.4. Academic achievement

We used standardized tests to assess mathematical and reading achievement. For mathematics, we used the two subtests of the “Heidelberger Rechentest”, namely, Sequences and Addition/Subtraction (HRT 1–4; Haffner, Baro, Parzer, & Resch, 2005). For reading, we used the “Salzburger Lese-Screening” (SLS; Mayringer & Wimmer, 2003) to assess reading comprehension and the “Würzburger Leise Lese Probe” (WLLP; Küspert & Schneider, 1998) to assess reading speed. In the subtest Sequences, children had to make out the rule that was applied within a sequence of six digits and thus continue the sequence according to this rule by adding the next three digits. The Addition/Subtraction task contained simple additions and subtractions. For reading, children had to judge the accuracy of sentences in the SLS and match the meaning of a noun with the appropriate picture in the WLLP. All academic achievement tasks were timed tasks and the dependent variables for all tasks was the number of correctly solved trials. In order to receive identical metrics, the dependent measures were z-standardized. The internal consistency of academic achievement tasks was $\alpha = .87$.

2.5. Statistical analyses

The descriptive statistics for all included variables are shown in Table 1. As mentioned above, all variables were z-standardized and inverted if needed to receive identical metrics for all measures. Further, outliers that deviated more than ± 3 standard deviations from the samples' mean were replaced with the value of the third standard deviation of the corresponding variable. Since there were only few missing values (less than 1% for each dependent variable), and because the missing values were completely at random, we

Table 1
Descriptive Statistics of the Included Variables.

	M (SD)	Min.–Max.
Executive Functions		
Backward Recall (correct answers)	9.29 (4.04)	0–18
Flanker Inhibition (Accuracy)	0.87 (0.17)	0.14–1.00
Flanker Shifting (Accuracy)	0.74 (0.18)	0.19–1.00
Visual-motor coordination		
Posting Coins (s)	37.93 (3.94)	28.27–54.89
Threading Beads (s)	38.48 (8.19)	26.49–90.00
Drawing Trail (errors)	4.01 (3.10)	0.00–16.00
Physical Fitness		
Six-Minutes-Run (m)	862.44 (183.57)	504.00–1578.00
Standing Long Jump (cm)	107.36 (16.64)	66.00–153.00
Jumping Sideways (correct trials)	37.58 (10.73)	8.00–69.00
School achievement		
Addition/Subtraction (correct answers)	6.26 (2.45)	1.00–12.00
Sequences (correct answers)	10.52 (2.82)	1.00–16.00
SLS (correct answers)	19.26 (9.57)	0.00–49.00
WLLP (correct answers)	57.36 (21.47)	0.00–125.00

Note. SLS = Salzburger Lese-Screening; WLLP = Würzburger Leise Lese Probe.

Table 2
Associations between the included tasks.

	t1									t_2			
	1	2	3	4	5	6	7	8	9	10	11	12	13
t_1													
Executive Functions													
1. Inhibition		.45**	.31**	.30**	.35**	.13	.22*	.23*	.32**	.33**	.35**	.28*	.31**
2. Shifting	.44**		.18*	.37**	.28*	.15	.24*	.15	.38**	.32**	.24*	.34**	.38**
3. Updating	.30**	.17*		.34**	.30**	.18*	.14	.10	.27*	.51**	.42**	.33**	.33**
Visual-Motor Coordination													
4. Posting Coins	.28*	.37**	.32**		.54**	.32**	.30**	.30**	.41**	.41**	.50**	.48**	.55**
5. Threading Beads	.33**	.27*	.27*	.51**		.29**	.13	.18*	.38**	.41**	.35**	.35**	.35**
6. Drawing Trail	.11	.15	.17	.30**	.26*		.09	.21*	.25*	.10	.19*	.22*	.26*
Physical Fitness													
7. Six-Minutes-Run	.20*	.23*	.11	.25*	.05	.06		.20*	.24**	.12	.16	.23*	.28**
8. Standing Long Jump	.21*	.14	.08	.28*	.15	.19*	.17		.44*	.04	.17	.09	.11
9. Jumping Sideways	.31**	.37**	.26*	.39**	.36**	.24*	.21*	.43**		.28**	.28**	.21*	.25*
t_2													
School Achievement													
10. Sequences	.31**	.32**	.50**	.38**	.38**	.07	.08	.01	.26*		.62**	.60**	.64**
11. Addition/Subtraction	.33**	.23*	.41**	.47**	.30**	.17*	.10	.14	.26*	.61**		.50**	.54**
12. Reading comprehension	.27*	.34**	.32**	.47**	.33**	.20*	.20*	.07	.19*	.60**	.48**		.90**
13. Reading speed	.30**	.37**	.31**	.52**	.31**	.24*	.24*	.09	.23*	.62**	.52**	.89**	

Note. Above the diagonal, Pearson correlations; below the diagonal, partial correlations controlling for chronological age. * $p < .05$; **; $p < .001$. t_1 and t_2 = measurement point 1 and 2, respectively.

used the Expectation Maximization Method to replace the missing values (Little, 1988; χ^2 = 44,36; df = 52; p = .79). For Structural Equation Modeling, we used AMOS 23 software (Arbuckle, 2014). A Structural Equation Model was computed (see Figure 1) to assess the longitudinal interrelations between visual-motor coordination, physical fitness and executive functions, as well as their predictive power on second grade academic achievement. We used a latent variable approach and for all variables, covariances between measurement errors were allowed. To describe the model fit, the Comparative Fit Index (CFI), the Tucker Lewis Index (TLI), the Root-Mean-Square (RMSEA) and the normed χ^2 were used. If the CFI and TLI were greater than .95, the RMSEA smaller or equal .06, and the normed χ^2 below 2, the model fit was considered as good (Byrne, 2001; Hu & Bentler, 1998).

3. Results

For a first overview, correlations between executive functions, visual-motor coordination, physical fitness in kindergarten, and academic achievement in second grade were computed on task level. The correlation coefficients are shown in Table 2. As expected, the three tasks within the same dimension (executive functions, visual-motor coordination, physical fitness) were substantially interrelated in kindergarten. Likewise, all academic achievement tasks were related to each other in second grade. Longitudinally, substantial correlation between executive functions, visual-motor coordination and later achievement were found (correlation coefficients being between r = .10 and r = .55). Thereof, only one correlation did not reach significance. On the task level, the relation between physical fitness and later achievement appears to be somewhat lower than for the other two constructs. All tasks were positively interrelated, but only half of the correlations reached significance (correlation coefficients being between r = .04 and r = .28). The partial correlations controlled for age are depicted below the diagonal. Obviously, controlling for age did not change the correlation pattern substantially. There were only minimal changes in the magnitude of the correlations, indicating that differences in age did not substantially influence the reported correlations. Hence, we did not control for age in the analyses reported below.

3.1. Confirmatory factor analyses

In a next step, a model with all four latent variables (visual-motor coordination, physical fitness, executive functions, academic achievement) associated with covariances was estimated. The model fit was good (χ^2 (58) = 88.64, $p < .01$; χ^2 normed = 1.53; CFI = 95; TLI = .94; RMSEA = .06). All indicators loaded significantly on the corresponding latent variable ($p < .05$) and all latent variables were significantly intercorrelated ($p < .05$) suggesting that these four constructs are empirically distinguishable, yet interrelated.

3.2. Structural equation modeling

The longitudinal relations between academic achievement and visual-motor coordination, physical fitness, and executive functions (using each variable as single predictor) were computed. Considered separately, each of the three constructs significantly predicted later academic achievement (visual-motor coordination: β = .73; physical fitness: β = .39; executive functions: β = .74;

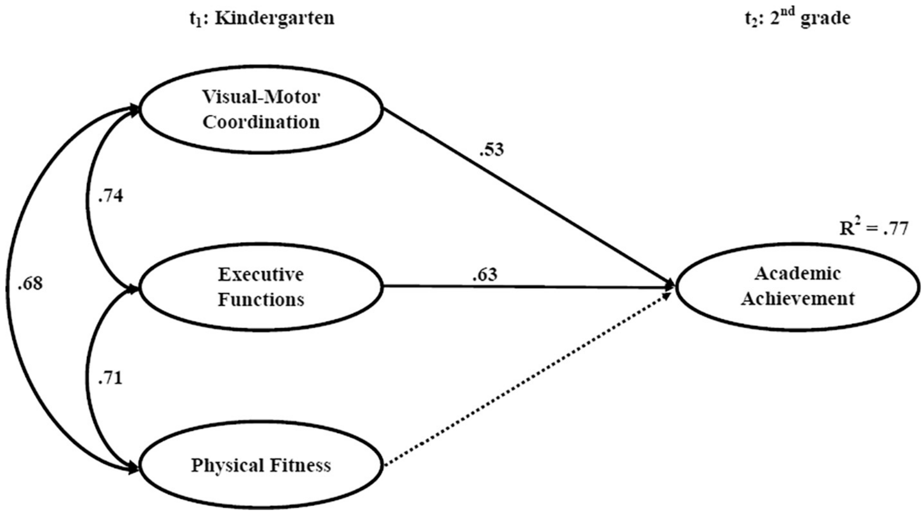

Figure 1. Longitudinal Relations Between the Latent Variables; all reported estimates are standardized and significant ($p < .05$).

ps < 0.05). In a next step, the cross-sectional associations between visual-motor coordination, physical fitness, and executive functions as well as their relative importance for early academic achievement were explored using latent variable structural equation modeling techniques. When all three constructs were entered simultaneously to predict later academic achievement, the model depicted in Figure 1 resulted. The model provided a good fit with the data (χ^2 (57) = 66.12, $p < .01$; χ^2 normed = 1.16; CFI = 98; TLI = .98; RMSEA = .04). The factor loadings of the single indicators on the corresponding latent variable are presented in Table 3; these were all significant. As can be seen, visual-motor coordination, executive functions, and physical fitness were all significantly intercorrelated with each other cross-sectionally in kindergarten ($p < .05$). Considering the three latent variables simultaneously in the model, executive functions ($\beta = .63$, $p < .05$) and visual-motor coordination ($\beta = .53$, $p < .05$) remained significant predictors of later academic achievement, while the path from physical fitness to later academic achievement was no longer significant.

Because there was no significant direct effect from physical fitness on academic achievement, the indirect path from physical fitness via executive functions was analyzed in a further step. This model is depicted in Figure 2. Bootstrapping procedures for every of the 2000 bootstrapped samples were operated, and bias-corrected 90% confidence intervals were computed. Figure 2 shows the indirect path from physical fitness via executive functions on academic achievement. The standardized indirect effect was .60. The confidence interval did not include zero (*range* = .29–2.17), and the indirect effect was statistically significant ($p < .05$). The factor loadings of the indicators on the used latent variables are shown in Table 3.

Because the strength of the direct path of visual-motor coordination on academic achievement was somewhat lower in the model in which all three construct were used simultaneously as predictors of later academic achievement, compared to the model in which visual-motor coordination was the only predictor, we computed the indirect path via executive functions for visual-motor coordination as well. For visual-motor coordination, a significant total effect was found ($\beta = .73$, $p < .05$), the confidence interval did not include zero (*range* = .62–.84). The path from visual-motor coordination to executive function ($\beta = .75$, $p < .01$) as well as the path from executive functions to academic achievement ($\beta = .47$, $p < .05$) were significant. However, the indirect effect did not reach significance and also the direct effect was not statistically significant (model's fit: χ^2 (30) = 42,74, ($p = .06$); χ^2 normed = 1.43; CFI = 97; TLI = .99; RMSEA = .06).

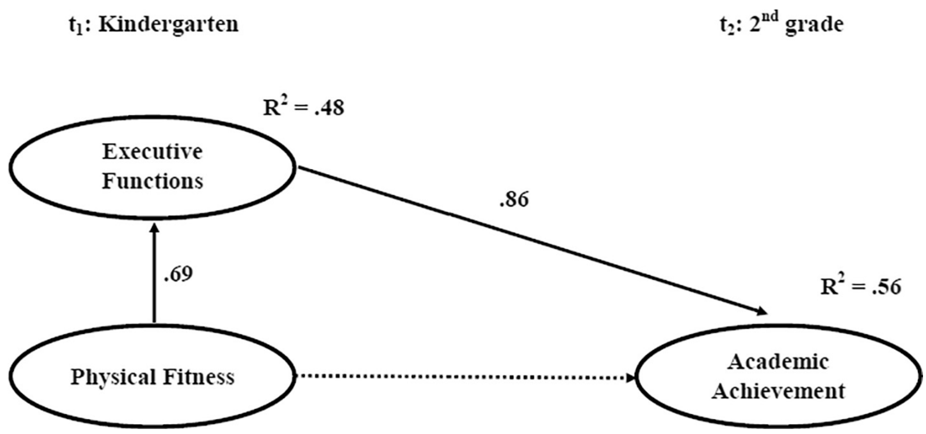

Figure 2. Indirect Path from Physical Fitness on Academic Achievement via Executive Functions (model's fit: χ^2 (30) = 48.80, ($p = .21$); χ^2 normed = 1.19; CFI = 98; TLI = .98; RMSEA = .04).

Table 3
Factor Loadings of the Indicators on the Latent Variables of the Model Depicted in Figure 1 and Figure 2.

Latent factor	Item	Factor loadings							
		1	2	1	2	1	2	1	2
Executive Functions	Inhibition	.61	.53						
	Shifting	.59	.52						
	Updating	.51	.55						
Visual-Motor Coordination	Posting Coins			.82					
	Threading Beads			.66					
	Drawing Trail			.39					
Physical Fitness	Six-Minutes-Run					.37		.35	
	Standing Long Jump					.54		.53	
	Jumping Sideways					.77		.81	
Academic Achievement	Addition/Subtraction							.73	.72
	Sequences							.79	.82
	SLS							.74	.71
	WLLP							.79	.77

Note. All indicators loaded significantly on their latent variable ($p < .05$). SLS = Salzburger Lese-Screening; WLLP = Würzburger Leise Leseprobe. 1 = Model depicted in Figure 1; 2 = Model depicted in Figure 2.

4. Discussion

The aims of the present longitudinal study were to investigate the influence of and the relationships between different domain-general predictors of academic achievement (executive functions, visual-motor coordination, and physical fitness) in 5- to 6-year olds (at the first time point), when entered in a model simultaneously. As expected, by including each construct separately as predictor for later academic achievement, each of the three constructs significantly predicted later academic achievement. In a model in which all three constructs were entered simultaneously to predict later academic achievement, however, only the direct influence of executive functions and visual-motor coordination remained significant. The relation between physical fitness and academic achievement appeared to be mediated through executive functions, while for visual-motor coordination direct and indirect effects via executive functions together seem to account for a significant total effect on later academic achievement.

Starting with a close look at the cross-sectional correlations, executive functions, visual-motor coordination, and physical fitness were positively correlated on task levels as well as on the level of latent variables. These results are in line with previous studies reporting substantial links between these constructs in typically developing children in a similar age-range using similar measures (e.g., Donnelly et al., 2016; Roebers et al., 2014; Wrotniak, Epstein, Dorn, Jones, & Kondilis, 2006). These findings also support Piaget's theoretical assumptions of a parallel development of the motor and cognitive domain. According to Piaget, children with better visual-motor coordination more often manipulate objects with their hands or are more motivated to learn new aspects of visual-motor coordination. If we imagine a child learning to knit or crafting a toy, it is obvious that not only visual-motor coordination but also cognitive processes, for example, remembering sequences of motor actions, are involved (Piaget & Inhelder, 1966). Similarly, physically fitter children more often engage in physical activities than physically less fit children (Ruiz et al., 2006), so that these children may also more often be engaged in an exploration of the environment or motor skill learning, which in turn may benefit their cognitive development.

From a neuropsychological point of view, the cerebellum, the prefrontal cortex, the basal ganglia and other connecting structures seem to be co-activated in motor as well as in cognitive tasks. Therefore, maturational differences in the functional and structural connectivity of these structures may serve as another explanation for the reported links (Diamond, 2000). A third explanation for the high interrelations between the constructs are shared higher order cognitive processes that are used to cope with the speed-accuracy trade-off that is inherent in most of the tasks used in this study and in most of children's daily life activities (Roebers & Kauer, 2009). Such processes may include forward planning, goal-orientation, and adaptations based on feedback loops, to name a few (Oberer et al., 2017).

Looking at the longitudinal relations on the task level, there seems to be a more consistent relation between executive functions and academic achievement, and between visual-motor coordination and academic achievement, than between physical and academic achievement. Comparably, on the level of latent variables, visual-motor coordination was found to be a stronger predictor for later academic achievement than physical fitness, but at the same time, all three constructs significantly predicted later academic achievement, when used as single predictors in the present approach. The strong relation between visual-motor coordination and academic achievement is in line with previous findings (Kim et al., 2017; Pitchford et al., 2016), suggesting that visual-motor coordination is of particular importance in the beginning of formal schooling. One possible explanation is that visual-motor coordination plays an important role while children learn to write. Assuming that learning to write means learning a new motor skill, according to Ackerman (1987), it can be expected that visual-motor coordination is of special importance in the initial phase of learning, when the skill is not automatized yet. Possibly, in this circumscribed period of learning to write, children with better visual-motor coordination are at an advantage compared to age mates with less well developed visual motor coordination. This advantage may decrease in the course of development, as soon as children automatize their writing skills. Another explanation suggested by Kim et al. (2017) is that visual-motor coordination is important for the development of visual-motor integration and therefore only indirectly linked to school achievement. Thus, in this specific period of development, not only visual-motor integration, but also visual-motor coordination seems to be important for later academic achievement underlining the general importance of fine motor skills as school readiness factor. Future studies may want to further address the specific contributions of visual-motor *integration* and *coordination* in the course of development.

The path coefficient from physical fitness to academic achievement is consistent in magnitude with the results of the Dutch cross-sectional study (van der Niet et al., 2014). Nevertheless, a direct comparison is difficult because different procedures and instruments were used. Even though, the overall pattern of the correlations found in the present study is consistent with the contemporary literature and suggests that physical fitness is longitudinally related to early academic achievement. This is an important finding as this goes beyond the well documented beneficial effects of physical fitness for mental and physical health across the life span.

The novelty of this study was to the inclusion of executive functions, visual-motor coordination, and physical activity simultaneously into one longitudinal prediction of academic achievement. As in previous studies (Roebers et al., 2014; van der Niet et al., 2014), the direct influence of both, visual-motor coordination and physical fitness to academic achievement decreased when executive functions were included into the model, and executive functions remained the strongest predictor. Hence, the importance of executive functions for later academic achievement was once more confirmed in the present study (Blair & Raver, 2015). Noteworthy, executive functions explained significant amounts of later academic achievement, over and above the influence of visual-motor coordination and physical activity, rendering executive functions to one of the most influential school readiness factors of the contemporary literature. Although the influence of visual-motor coordination decreased in the model with all three predictors, visual-motor coordination still explained a significant amount of variance in academic achievement, over and above the influence executive functions, underlining the importance of visual-motor coordination for later academic achievement, at least in this specific age group. It seems thus safe to assume that visual-motor coordination is a substantial school readiness factor and should not be overlooked.

The reported significant indirect paths from physical fitness to academic achievement via executive functions confirm the meditational role of executive functions in the relation between physical fitness and academic achievement. The results of this longitudinal study stress previous findings of a meditational role of executive functions in cross-sectional studies in children and adolescents (Rigoli et al., 2012; van der Niet et al., 2014) and extend the evidence to a true longitudinal effect. This result is in line with the cognitive stimulation hypothesis: Sport or physical activities not only have high coordinative demands, but physical activities also trigger or call for children' executive functions (planning ahead, keeping their goal in mind, adapt to changing environments). Consequently, children implicitly practice their executive functions by performing physical activities or challenging coordinative tasks (e.g., Best, 2010; Moreau et al., 2015; Tomporowski, McCullick, Pendleton, & Pesce, 2015). This seems to be especially the case when tasks are new and complex (Moreau & Conway, 2013; Pesce et al., 2016; Roebers & Kauer, 2009). Results from intervention studies showing that physical activities with a higher cognitive demand are more efficient to improve executive functions than aerobic training with few cognitive demands strengthen this assumption additionally (Koutsandréou, Wenger, Niemann, & Budde, 2016; Pesce et al., 2013; Schmidt et al., 2015).

Similar mechanisms seem plausible when children learn new visual-motor coordination skills: Solving new visual-motor coordination tasks could be cognitively demanding and therefore a means to enhance executive functions. However, the indirect path from visual-motor coordination to academic achievement via executive functions could not be confirmed statistically, at least not in the present study. Further research integrating additional variables like visual-motor integration or writing speed is necessary to clarify the mechanisms behind the reported relations between visual-motor coordination and academic achievement.

Even though the study had a longitudinal design, it must be admitted that executive functions, visual-motor skills and physical fitness were measured at the same time point. Hence, no firm conclusions about causality can be drawn.

To conclude, the present study underlines the importance of executive functions for early academic achievement. In addition to the strong direct effect, executive functions also contribute to the indirect effect that physical fitness has on academic achievement. Importantly, the significance of visual-motor coordination for later academic achievement was underlined by the finding that visual-motor coordination explained a significant amount of variance, while simultaneously estimating the effects of executive functions and physical fitness. Not only visual-manual integration (closely linked to "penmanship" and thus early academic achievement) but visual motor coordination itself should thus be considered as school readiness factor. The mechanisms explaining these longitudinal relations between visual-motor coordination in kindergarten and early academic achievement should be further investigated. The influence of physical fitness on academic achievement could be clarified by showing that this seems to be an indirect effect via executive functions. This is not to say that physical fitness is negligible. Rather, any child appropriate (ideally fun) activity that – as a by-product – triggers executive functions can be considered as positive for a productive youth development.

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