Trends in Neuroscience and Education 34 (2024) 100220

Contents lists available at ScienceDirect

Trends in Neuroscience and Education

journal homepage: www.elsevier.com/locate/tine

Developmental associations of fundamental motor skills and executive functions in preschoolers — The role of the physical activity and the effects on early numeracy

Anssi Vanhala [a,*], Anna Widlund [b], Johan Korhonen [b], Eero A. Haapala [c,d], Arja Sääkslahti [c], Pirjo Aunio [a]

[a] Faculty of Educational Sciences, University of Helsinki, Finland
[b] Faculty of Education and Welfare Studies, Åbo Akademi University, Vaasa, Finland
[c] Faculty of Sport and Health Sciences, University of Jyväskylä, Finland
[d] Institute of Biomedicine, School of Medicine, University of Eastern Finland, Finland

ARTICLE INFO

Keywords:
Development
Early numeracy
Executive functions
Motor skills
Physical activity
Preschool

ABSTRACT

Background: Physical activity, fundamental motor skills, executive functions and early numeracy have shown to be related, but very little is known about the developmental relations of these factors.

Procedure: We followed 317 children (3–6 years) over two years. Fundamental motor skills and executive functions (inhibition+switching, updating) were measured at all time points (T1, T2, T3) and physical activity at T1 and early numeracy at T3.

Main findings: Children with better fundamental motor skills at T1 developed slower in inhibition and switching. Fundamental motor skills developed faster in children who had better initial inhibition and switching ability. Vigorous physical activity at T1 was associated with a weaker initial inhibition and switching. The initial level and the developmental rate of updating were related to better early numeracy skills.

Conclusions: Findings indicate that fundamental motor skills and executive functions are developmentally related, and updating is an important predictor for early numeracy in preschoolers.

1. Introduction

Executive functions represent higher order cognitive processes necessary for goal-directed behavior [1] that are also important predictors of later academic performance [2] and for early numeracy [3]. Previous studies have linked physical activity and fundamental motor skills to executive functions [4,5] and early numeracy [6] in preschoolers. At the same time, evidence of insufficient levels of physical activity [7,8], high levels of sedentary time [9], and decline in motor skills [10] in preschoolers has raised concerns, as sedentary behavior has been associated with weaker cognitive and academic skills already in early childhood [11]. However, there are no prior studies examining developmental associations between physical activity, fundamental motor skills, executive functions and early numeracy through the rate of change. Several domain-specific (i.e., cognitive) but also domain-general (e.g., physical) factors have an impact on a child's overall and cognitive development [12], and therefore more holistic study designs are required to better understand the developmental interrelations between various factors in early childhood. This knowledge has theoretical and practical implications, as it helps to understand development in early childhood, but also potentially offers new opportunities for instructions and intervention to support cognitive development. Therefore, the aim of this study was to examine developmental relations between physical activity, fundamental motor skills, executive functions and early numeracy among 3–6-year-old preschoolers.

1.1. Developmental associations between executive functions and fundamental motor skills

The period of 3–6 years is critical for the development of executive functions [1] and fundamental motor skills [13]. According to Miyake et al. [14], executive functions consists of three main components: inhibition (ability to inhibit automatic responses), switching (ability to move between multiple tasks, operations, or mental sets), and updating

* Corresponding author.
E-mail address: anssi.vanhala@helsinki.fi (A. Vanhala).

https://doi.org/10.1016/j.tine.2024.100220
Received 8 November 2023; Received in revised form 30 December 2023; Accepted 11 January 2024
Available online 15 January 2024

(monitoring, and coding upcoming information, and refreshing information in mind). Fundamental motor skills are a group of important skills for later motor development, daily life functioning, and participation in context-specific physical activities [13,15,16]. Fundamental motor skills can be divided into three different components: locomotor (e.g., running and jumping), object control (e.g., throwing and catching) and stability skills (e.g., balancing and twisting) [17].

Fundamental motor skills and executive functions have been proposed to be intertwined as motor and cognitive tasks require the same underlying processes including processing information, organization of behavior, attention to the task, and inhibition of irrelevant stimuli [18,19]. Furthermore, executive functions and fundamental motor skills are related in human behavior in everyday life as executive functions are important for directing behavior, and motor skills are needed to implement actions in practice [20]. Evidence from neuroimaging studies supports the interrelation of these factors as brain areas important for executive functions (prefrontal cortex) and fundamental motor skills (cerebellum) have been found to support each other, and impairment in one system have been found to affect negatively also to the other [21,22].

Previous studies have supported this interrelation, reporting that intervention including fundamental motor skill training might be beneficial for cognitive development (including executive functions) and academic learning in children aged 3–7 years [23]. Cross-sectional studies among preschoolers have provided evidence that fundamental motor skills are associated with inhibition [24], updating [25] and overall executive functions performance [26,27]. In longitudinal studies, positive predictive associations between fundamental motor skills and updating [28,29] and overall executive functions performance [30] have been reported among preschoolers. In a study by Piek et al. [29], fundamental motor skills assessed among four-year-olds with a parental questionnaire predicted updating and processing speed later, in school age. In another study, fundamental motor skills at the baseline were associated with improved updating over nine months [28] among 4–5-years old preschoolers. However, Zysset et al. [31] did not find longitudinal associations between fundamental motor skills and executive functions when investigating several predictors for executive functions (inhibition and updating). The relation between the development rates of fundamental motor skills and executive functions has only been investigated among preschoolers in one previous study where Willoughby et al. [30] found that improvements in motor skills were associated with improvements in composite score of executive functions (inhibition, switching, and updating) in 3–5-years old children. However, in their study, both fine motor skills and fundamental motor skills measures were included in the same factor, thus no conclusions could be drawn about how fundamental motor skills independently affects executive functions.

1.2. Physical activity, executive functions and fundamental motor skills as predictors for early numeracy

Early numeracy, including numerical relational and counting skills, is a set of mathematical skills foundational for later mathematical and academic performance [32]. Different components of executive functions can influence early numeracy performance in several ways [33]. For instance, updating is vital to the storage and retrieval of partial results when performing the tasks, inhibition suppresses inappropriate strategies for solving mathematical tasks, whereas switching ability helps to switch between changing tasks [33]. Executive functions have been positively associated with early numeracy in several cross-sectional [34,35] and longitudinal studies [3,36,37] in preschoolers. In previous longitudinal studies, inhibition and switching [36], updating [37] and combined updating -inhibition factor [3] have been found to predict later mathematical performance.

A few studies have examined the relationship between fundamental motor skills and early numeracy. In these studies, better fundamental motor skills have been found to be cross-sectionally associated with better early numeracy [26,38]. Moreover, improvements in a combined factor for fundamental motor skills and fine motor skills have been associated with improvements in early numeracy [30]. In one previous cross-sectional study, fundamental motor skills were found to be associated with early numeracy through updating [25].

In addition to motor skills, the amount of physical activity has been suggested to be beneficial for executive functions, especially in older children [39]. Physical activity is defined as any bodily movement produced by skeletal muscles that results in energy expenditure [40], and is typically operationalized as time spent in different intensity levels (light, moderate or vigorous) [41,42]. In practice, vigorous physical activity includes activities such as running, jumping or climbing. Examples of moderate physical activity are brisk walking, riding a bike or playing with a ball. Physical activity is defined to be light when a child strolls, or is throwing and catching a ball or dressing up. The term moderate-to-vigorous physical activity refers to the time spent in both moderate and vigorous physical activity. Moderate-to-vigorous physical activity has been used in the majority of previous studies investigating associations between physical activity and executive functions among preschoolers [e.g. 30,31,43,44].

Physical activity might be beneficial for development of executive functions as it has been shown to lead to physiological changes in the brain regions (i.e. prefrontal cortex, hippocampus, basal ganglia, and cerebellum) that are critical for learning, memory and executive functions [39]. These physiological changes include improved neural structures and functions [45], changes in neurotrophic factors and neurotransmitter concentrations, and increases in cerebral blood flow [46]. In addition to direct neurophysiological changes, it has been proposed that physical activity has an impact on executive functions through the cognitive demands of goal-directed and engaging exercise (e.g., group activities) and the cognitive engagement required to perform complex motor movements [39].

Previous reviews have provided some preliminary evidence of relation between physical activity and cognitive outcomes in preschoolers although the results have been reported to be mixed in previous studies [4,47,48]. The findings concerning the associations between different intensity levels of physical activity and executive functions in preschoolers have been inconsistent. Most previous studies have examined associations between moderate-to-vigorous physical activity and executive functions. In these studies, positive [44], negative [24,49] and non-significant [43] cross-sectional associations have been reported. In a study by Zyssett et al. [31], longitudinal associations between moderate-to-vigorous physical activity and executive functions (inhibition and updating) were not found in 2–6-years-old preschoolers. Moderate and vigorous physical activity have been investigated separately in some previous studies. Vigorous physical activity have been found to be positively associated with updating [41] and to predict improvements in shifting in 3–6-years old children [42]. In addition, intervention studies have provided evidence that increased physical activity has beneficial effects on cognitive development (including executive functions) in preschoolers [50]. However, findings have been mixed as vigorous physical activity has been also found to be associated with weaker inhibition and switching in this age group [25]. No associations have been found between moderate physical activity and executive functions in previous cross-sectional [24,25,41] and longitudinal studies [42].

Previous studies have also suggested that executive functions mediates beneficial effects of physical activity on academic skills [51,52]. One may also hypothesize physical activity to be beneficial for early numeracy through better fundamental motor skills as increased levels of physical activity has been suggested to support the development of fundamental motor skills in early years through movement experiences [53], and previous studies have provided evidence that physical activity predicts better fundamental motor skills [54,55]. However, there are very few studies examining these mediating roles in preschoolers.

Becker et al. [56] found that moderate-to-vigorous physical activity during recess outdoor play during preschool hours was associated with early numeracy through inhibition. Recently, fundamental motor skills and updating were found to be mediators in positive cross sectional associations between vigorous physical activity and early numeracy [25]. However, inhibition and switching mediated the negative association between vigorous physical activity and early numeracy. Thus, previous evidence on the mediating role of executive functions and fundamental motor skills among preschoolers is scarce, has been based on cross-sectional study design, and findings have been mixed.

1.3. Current study

Previous studies have shown some positive associations between physical activity, fundamental motor skills, executive functions and early numeracy among preschoolers [25,28,42,50]. However, there are some gaps in previous research, which this study aims to address.

Prior longitudinal studies have examined predictive relations between fundamental motor skills and executive functions [e.g., 28,31]. Furthermore, intervention studies have offered evidence that growth in fundamental motor skills is associated with improvements in executive functions [23]. However, there is no previous evidence of whether initial level and growth of fundamental motor skills and executive functions are associated over a longer period of development in preschool years. Therefore, in the present study, developmental associations between fundamental motor skills and executive functions over two years were examined.

In addition, as pointed out in a recent review [5], despite the well-known interrelation between physical activity and fundamental motors skills [55,53], there are very few studies investigating these both together with executive functions. There is preliminary evidence that improvements in physical activity lead to improvements in motor skills and cognition [50]. However, previous studies have not investigated how physical activity influences on the development of fundamental motor skills and executive functions. Therefore, the role of physical activity for the development of fundamental motor skills and executive functions was investigated.

Moreover, executive functions and fundamental motor skills have been found to mediate cross-sectional associations between physical activity and early numeracy among preschoolers [25], but relations between these factors have not been tested with longitudinal study designs. Thus, the relations of physical activity, fundamental motor skills, executive functions to early numeracy over two years were tested in the current study.

This novel knowledge expands the understanding of the associations between physical activity, fundamental motor skills, executive functions and early numeracy during preschool years, and has clear theoretical and practical implications as it provides a basis for interventions and educational practices [5]. Thus, the aim of this study was to examine the developmental relations between physical activity, fundamental motor skills, executive functions, and early numeracy over two years.

The following research questions were addressed:

1. How do fundamental motor skills and executive functions develop in preschoolers over two years?
We expect that fundamental motor skills [17] and executive functions [1] develop significantly over time and that there are individual differences in the development (H1).
2. How are levels and changes in fundamental motor skills and executive functions related to each other?

Based on the previous findings of relations between fundamental motor skills and executive functions [24–30], we expected to find positive associations between the level and change of fundamental motor skills and executive functions (H2). In other words, that higher fundamental motor skills would be associated with both higher initial level and more positive development in executive functions, and vice versa.

3. How does physical activity predict the level and change in fundamental motor skills and executive functions?

We hypothesized that physical activity is positively associated with fundamental motor skills (H3.1) [24,55]. Based on previous findings that physical activity predicts executive functions over time [42] and physical activity interventions are beneficial for cognition [50], we hypothesized that physical activity is positively related to change in executive functions over time (H3.2).

Due to the mixed previous cross-sectional findings [5] on the relations between physical activity and executive functions, we do not set specific hypothesis regarding the relation between the physical activity and level of executive functions.

4. How does the level and change in fundamental motor skills and executive functions predict early numeracy?

We expected to find the positive associations of fundamental motor skills (H4.1) [26,30] and particularly executive functions with early numeracy (H4.2) [3].

5. How does the level and change in fundamental motor skills and executive functions mediate the relation between physical activity and early numeracy?

Based on findings from previous cross-sectional studies, we hypothesized that fundamental motor skills and executive functions mediate the association between physical activity and early numeracy over time (H5) [25,56].

2. Methods

2.1. Study design and study population

This longitudinal study was part of the larger Active Early Numeracy Study. The participants were recruited from 15 preschools in the metropolitan area of Finland in October 2019. Parents filled out a consent form where they gave permission for children to participate in the study, and they were required to ask children for oral permission as well. Children were informed that participation is voluntary and they can withdraw at any point. The University's ethics committee approved the study protocol. A total of 317 children (143 boys, 162 girls) participated in this study. The mean age of the children was 4.5 (SD = ±0.6) years at T1, 5.4 (SD = ±0.6) at T2 and 6.4 (SD = ±0.6) at T3. Data were collected across two years with three measurement points approximately one year between the measurements. executive functions and fundamental motor skills were measured at each time point (T1, T2 and T3), while physical activity and early numeracy were only measured at T1 and T3, respectively.

The time between measurements was planned to be one year, but due to the COVID19-outbreak, the time between the measurement points varied. The time between measurements was 11.1 (SD = ±4.0) and 12.9 (SD = ±3.2) months for fundamental motor skills, and 6.8 (SD = ±2.9) and 11.7 (SD = ±2.8) months for updating between T1- T2 and T2- T3, respectively. Due to technical issues with test computers, we were able to start measuring executive functions at T1 half a year later than fundamental motor skills, which explains the shorter time between T1 and T2 in executive functions measures compared to fundamental motor skills. This was accounted for when specifying the time factors in the growth models.

2.2. Study protocol

The assessments of fundamental motor skills, executive functions and early numeracy were conducted in their own sessions during regular preschool hours. Fundamental motor skills were assessed in groups of two or three children. The assessments for executive functions and early numeracy were conducted individually in a separate quiet room. Trained research assistants performed all the assessments. Physical activity data were collected with accelerometers during waking hours over seven consecutive days after all other assessments were performed.

2.3. Measures

2.3.1. Physical activity

Physical activity was measured using waist-mounted Actigraph wGT3X-BT accelerometers (ActiGraph, Pensacola, FL, USA). The monitor was attached to the right side of the hip using an elastic belt. Parents were instructed that children should wear the accelerometer during waking hours over seven consecutive days and remove them only during water-based activities. Non-wear time was defined as ≥ 20 min of consecutive "zero" counts [57]. Data were included in the analyses if the children had 480 min of data on at least three days [58]. Data were collected using 100 Hz sampling frequency and raw data were then reintegrated in the 15 s epochs using ActiLife software (version 6.13.4). The time spent in moderate and vigorous intensity levels was defined using age-appropriate cut points: ≥ 1680 counts/min for moderate physical activity and ≥ 3368 counts/min for vigorous physical activity [59]. To minimize the effect of wearing time, the percentage of time spent in moderate and vigorous physical activity in relation to wearing time were calculated and used in the analysis. Time spent in moderate, vigorous and moderate-to-vigorous physical activity (moderate and vigorous physical activity combined) were analyzed separately as previous studies have shown that especially these intensity levels are particularly beneficial for and differently associated with executive functions [41,42] and fundamental motor skills [55,60] among preschoolers.

2.3.2. Fundamental motor skills

Fundamental motor skills were measured with jumping sideways task from KTK-test [61]. In this task, children were instructed to jump sideways from side to side over a small wooden obstacle (60 cm × 4 cm × 2 cm) as many times as possible during 15 s. Five practice jumps were performed before test performance to verify that the child had understood instructions. The number of the correct jumps in two trials were summed as the total score of the task and was used in the analyses. The jumping sideways task was used as a measure of fundamental motor skills because it was found to be the best describe overall fundamental motor skills (including tasks measuring all three components of fundamental motor skills) in this sample. The jumping sideways task has also used as an indicator of fundamental motor skills in previous studies [62].

2.3.3. Executive functions

Executive functions were assessed by using two computer-based tests programmed using the ePrime software (Psychology Software Tools, Pittsburgh, USA). Two different components of executive functions, combined inhibition and switching, and updating, were assessed. This construct for executive functions has been previously found to exist in preschoolers [63], and in this sample [64]. The Simon task (modified from Davidson et al.) [65] was used to assess inhibition and switching, and the Pictorial Updating [63] task to assess updating. These tasks were selected to measure executive functions as the Simon task was previously shown to be the strongest indicator for inhibition and switching in this sample [64], and the Pictorial Updating task has been shown to be an appropriate measure for updating component in preschoolers [63].

In the Simon task, a butterfly or a frog were presented on the left or the right side of a computer screen. Children were instructed to take the butterfly and the frog home as quickly as possible by pressing a button with a picture of the corresponding animal. There was a picture of the butterfly on the left side and a picture of a frog on the right side of the keyboard. The pictures were presented either on the same side (congruent trial) or on the opposite side (incongruent trial) as the button with the picture of the corresponding animal. Children were administered a block of 25 incongruent trials followed by another block of 25 congruent trials. These two pure incongruent and congruent blocks were followed by four blocks of 21 trials, where congruent and incongruent tasks were mixed. Congruent and incongruent conditions included tasks from pure blocks of incongruent and congruent trials. Switch condition included tasks from mixed blocks involving conditional switches (incongruent-congruent or congruent-incongruent). Data was first cleaned at the subject level by using trial-by-trial response time data from each condition. Response times that differed by more than 3 SDs from the individual mean in each condition were deleted. Response times of less than 250 ms were treated as anticipatory responses and were deleted. After subject level cleaning, mean response time for correct responses in each condition (congruent, incongruent, no-switch and switch) was calculated. Finally, mean response time using response times from four different conditions were calculated and was used as an indicator for inhibition+switching in the analyses. Data were included in the analyses only if there were at least 75 % of correct responses in a congruent block and at least seven correct responses in each condition. The test showed good internal consistency in this sample at each time point (α = .85–.92).

In the Pictorial Updating task, a varying number of animal pictures (two to six) were shown one at a time on the computer screen. Children were asked to recall a specified number (1 to 3) of animals that were presented last on the screen. Pictures of all animals were presented on the screen and children were asked to select the correct animals by pressing the pictures on the screen in the same order as they had been presented. There were three blocks with six trials in each. Children had to recall: one animal in the first block, two animals in the second block and three animals in the third block. The number of animals presented in each trial varied from two to four in the first block, three to five in the second block and four to six in the third block. One point was given for each animal recalled in the same order as presented on the screen. In the pictorial Updating task, the accuracy scores were used in the analyses. The test showed good internal consistency in this sample (α = .78–.88).

2.3.4. Early numeracy

Early numeracy was measured using the Early Numeracy Test [66], which included a total of 40 items. The test measures numerical relational (comparison, classification, one-to-one correspondence, seriation) and counting (using number words, synchronous and shortened counting, resultative counting, and general knowledge of the numbers) skills. The administrator presented the tasks and provided the test materials (pictures, cubes, paper, and pencil) according to the instructions. In every item, one point was given for a correct answer and zero for an incorrect answer, resulting in 40 as the maximum score. Sum score for early numeracy were used in the analysis. The test showed good internal consistency in this sample (α = .89).

2.4. Statistical analysis

2.4.1. Preliminary analyses

All data were first screened for missing values, outliers, and normality of distribution. Little's MCAR test [67] showed that data is missing completely at random ($\chi 2$ (411) = 439,790, p = .158). Mean values that differed by more than 3 SD from the age group mean were treated as outliers, and were replaced by values at 3 SD. Descriptive statistics and correlations of all measures at each time point were calculated. Independent samples *t*-test was conducted to compare sex differences in each variable. The skewness values for vigorous physical activity T1 (1.02) and inhibition+switching T1 (1.12) exceeded one suggesting skewed distribution in these variables. Therefore, the Mann-Whitney U test was used to test sex differences in these variables and Spearman's rank correlation to calculate the correlations between these variables.

When more than one task is used to measure one factor over time, the test of measurement invariance is needed to ensure that the construct measured is the same across time [68]. As four indicators (response time

Table 1
Model fit indices for measurement invariance testing for the Simon task.

Model	Constraints	*χ*2	*df*	RMSEA	CFI	TLI	ΔRMSEA	ΔCFI
1	Configural: no constraints	96.645	39	.072	.974	.956	–	–
2	Factor loadings	125.36	45	.079	.964	.947	.007	.01
3	Intercepts	137.265	51	.077	.961	.950	.002	.003

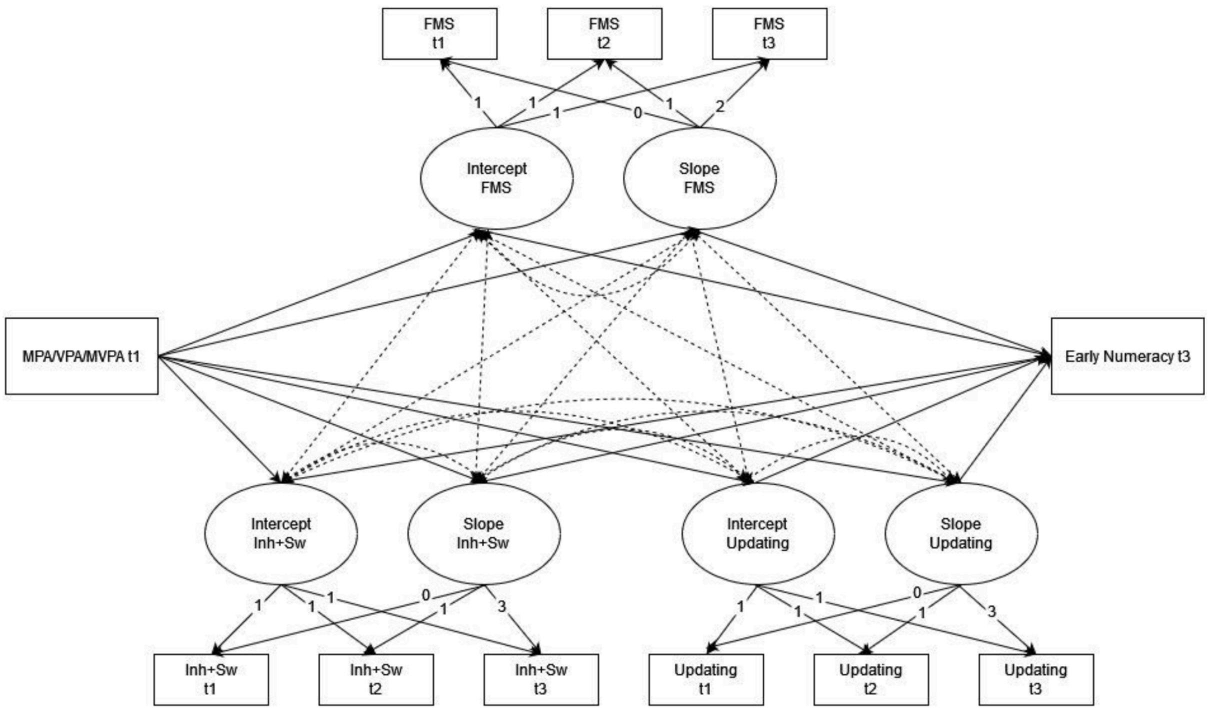

Fig. 1. The structure of models tested. Three different models were constructed: 1) Moderate, 2) Vigorous, 3) Moderate-to-vigorous physical activity as a predictor. Note. FMS = Fundamental motor skills, Inh+Sw = Inhibition and Switching, MPA = Moderate physical activity, MVPA = Moderate-to-vigorous physical activity, T1 = Time point 1, T2 = Time point 2, T3 = Time point 3, VPA = Vigorous physical activity

from congruent, incongruent, switch and no-switch condition) were used to construct composite scores for inhibition+switching, measurement invariance was tested with longitudinal confirmatory factor analyses (LCFA). LCFA included three phases. First, a configural model was constructed, where four conditions from the Simon task were used as indicators for one latent factor for inhibition+switching at each time point. In the second step, the factor loadings were constrained to be equal across time points. In the third step, intercepts and factor loadings were constrained to be equal over time. The comparative Fit Index (CFI; cut-off values close to > .9), Tucker Lewis Index (TLI > .9), Root Mean Square Error of Approximation (RMSEA < .08) and maximum likelihood (ML) -based standardized root mean squared residual (SRMR < .06) were used as criteria for acceptable model fit in all analysis [69,70]. The measurement invariance across time is achieved if there is a change of less than 0.01 in CFI and 0.015 in RMSEA between models tested [68]. All three models tested showed an acceptable model fit to the data. There were no significant differences between the models (Table 1) indicating that there are no differences in the factor structure over three time points [67]. It was not possible to conduct LCFA for fundamental motor skills or updating as only one task was used to measure these factors.

2.4.2. *Main analyses*

The main analyses were conducted using Mplus version 8.6 [71]. First, a linear growth curve model, including measures of fundamental motor skills and executive functions, was fitted to the data to answer the first and second research questions on the developmental associations between fundamental motor skills, inhibition+switching and updating over two years. The loadings of the observed variables on the slope factor across time points 1 to 3 were fixed to 0, 1, and 2 for fundamental motor skills, and 0, 1, and 3 for inhibition+switching and updating, to account for the time differences between measurements. The loadings were different for fundamental motor skills and executive functions as for executive functions time between T1 and T2 (approximately half a year) was shorter than between T2 and T3 (approximately a year), while time between each time point was approximately one year for fundamental motor skills. To make the values easier to interpret, reaction times of executive functions were divided by one hundred by using the define command in Mplus.

In the next phase to answer research questions three to five, physical activity at T1 (moderate, vigorous and moderate-to-vigorous physical activity) was added to predict fundamental motor skills and executive functions, and early numeracy at T3 was added to be predicted by fundamental motor skills and executive functions (Fig. 1). To test how different physical activity intensity levels are related to the development of fundamental motor skills and executive functions, separate models for moderate, vigorous and moderate-to-vigorous physical activity were constructed. As the age of children within a time point was found to be associated with physical activity and early numeracy, age-controlled variables for moderate, vigorous, moderate-to-vigorous physical activity at T1 and early numeracy at T3 were calculated by regressing age at time of measurement on test scores and by saving the standardized residuals of the regression as new variables. Full information maximum likelihood estimation was used in all analyses.

Table 2
Descriptive statistics for all measures.

Variable	Time point 1						Time point 2						Time point 3					
	Total		Boys		Girls		Total		Boys		Girls		Total		Boys		Girls	
	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)
Physical activity																		
MPA (% of wearing time)	219	10.7 (2.4)	106	11.4 (2.3)	113	10.1 (2.3)***	–	–	–	–	–	–	–	–	–	–	–	–
VPA (% of wearing time)	219	4.3 (2.0)	106	4.6 (2.1)	113	4.1 (1.9)*	–	–	–	–	–	–	–	–	–	–	–	–
MVPA (% of wearing time)	219	15.1 (4.0)	106	16.0 (4.0)	113	14.1 (3.8)***	–	–	–	–	–	–	–	–	–	–	–	–
Fundamental motor skills																		
Jumping sideways (jumps)	248	20.0 (8.7)	114	19.7 (9.1)	134	20.3 (8.4)	265	25.2 (10.2)	125	24.5 (10.2)	140	25.8 (10.2)	254	33.0 (11.5)	119	32.7 (11.9)	135	33.2 (11.1)
Executive functions																		
Inhibition + Switching (the Simon task, mean response time)	165	1083 (249)	76	1043 (232)	89	1117 (258)*	240	1022 (243)	112	1013 (240)	128	1029 (246)	234	814 (157)	112	807 (160)	122	820 (154)
Updating (Pictorial Updating task sum score)	179	10.8 (5.3)	86	10.5 (5.3)	93	11.0 (5.3)	244	13.2 (5.9)	115	12.3 (5.7)	129	14.0 (6.0)*	255	16.8 (6.9)	123	16.1 (6.8)	132	17.5 (7.0)
Early numeracy																		
Early numeracy test (sum score)	–	–	–	–	–	–	–	–	–	–	–	–	244	28.3 (7.3)	118	28.3 (7.0)	126	28.2 (7.6)

Note. MPA = Moderate physical activity, MVPA = Moderate-to-vigorous physical activity, VPA = Vigorous physical activity. Statistically significant differences between the boys and girls are marked with an asterisk: ***$p < .001$, ** $p < .01$,* $p < .05$.

3. Results

The descriptive statistics for each measure at each time point are presented in Table 2. The T-test showed that there were sex differences in the amount of moderate, vigorous and moderate-to-vigorous physical activity, response time in the inhibition and switching task at T1, and number of the correct responses in the updating task at T2. Boys spent more time in moderate, vigorous and moderate-to-vigorous physical activity, and had faster response times in inhibition+switching tasks than girls. Girls outperformed boys in updating at T2.

Correlations between each measure at each time point are presented in Table 3. Vigorous and moderate-to-vigorous physical activity was positively related to fundamental motor skills at each time point. Vigorous physical activity was related to faster response time in inhibition and switching task at T1 and T3, and to better updating at T1. Fundamental motor skills were related to better performance in executive functions at each time point, and to EN at T3. Performance in inhibition and switching, and updating at each time point were positively related to EN at T3.

3.1. *The development of fundamental motor skills and executive functions (RQ1)*

The linear growth model for fundamental motor skills, inhibition+switching and updating fitted the data well [$\chi2$ (19) = 39.708, p = .0036, CFI = .971, TLI = .945, RMSEA = .060, SRMR = .057]. The growth of each factor over three measurement points is shown in Fig. 2. As presented in Table 4, the model showed that the slopes of fundamental motor skills, inhibition+switching, and updating were significant. The results revealed that the development of all factors were positive, meaning that scores in both fundamental motor skills and updating tasks improved over time and that children became faster in inhibition+switching tasks. Significant variance were also found in the initial levels and slopes of fundamental motor skills, inhibition+switching, and updating meaning that there were individual differences in performance at T1 and in the rate of the development in all factors.

3.2. *Relations between level and growth of fundamental motor skills and executive functions (RQ2)*

The results from the growth model (Fig. 3) showed that fundamental motor skills, inhibition+switching and updating were significantly associated with each other at T1. Better initial performance in fundamental motor skills was associated with faster response time in inhibition+switching and higher scores in the updating task at T1. Faster response time in the inhibition+switching task was also associated with higher scores in updating.

Regarding the developmental relations we found that better performance in fundamental motor skills, inhibition+switching and updating at T1 were related to slower development in inhibition+switching. In addition, better performance in inhibition+switching at T1 was related to faster development in fundamental motor skills. There were no relations between the development rate of FMSfundamental motor skills, inhibition+switching and updating.

3.3. *The relations of physical activity to fundamental motor skills and executive functions (RQ3)*

In the next phase, physical activity at T1 (moderate, vigorous, and moderate-to-vigorous physical activity in separate models) and early numeracy at T3 were included in the model (Fig. 1). These models were used to answer the research questions three to five on relations of physical activity to fundamental motor skills and executive functions, and fundamental motor skills and executive functions to early numeracy.

Table 3
Bivariate correlations.

	MPA T1	VPA T1	MVPA T1	FMS T1	FMS T2	FMS T3	Inh+Sw T1	Inh+Sw T2	Inh+Sw T3	UPD T1	UPD T2	UPD T3	EN T3
MPA T1	–												
VPA T1	.676***	–											
MVPA T1	.915***	.897***	–	.									
FMS T1	.078	.278***	.167*	–	.								
FMS T2	.097	.211*	.173*	.745***	–								
FMS T3	.090	.264***	.170*	.632***	.680***	–							
Inh+Sw T1	.022	−.185*	−.076	−.381***	−.310***	−.421***	–						
Inh+Sw T2	.047	.094	−.043	−.376***	−.396***	−.368***	.534***	–					
Inh+Sw T3	−.004	−.164*	−.068	−.384***	−.393***	−.393***	.571***	.426***	–				
UPD T1	−.025	.175*	.057	.371***	.293***	.221**	−.244**	−.191*	−.379***	–			
UPD T2	−.056	.013	−.032	.303***	.327***	.268***	−.285***	−.305***	−.266***	.414***	–		
UPD T3	−.002	.045	.008	.367***	.282***	.223***	−.226**	−.251***	−.350***	.400***	.522***	–	
EN T3	−.054	.010	−.053	.438***	.342**	.296***	−.305***	−.329***	−.369***	.488**	.509***	.676***	–

Note. EN = Early numeracy, FMS = Fundamental motor skills, Inh+Sw = Inhibition and switching, MPA = Moderate physical activity, MVPA = Moderate-to-vigorous physical activity, T1 = Time point 1, T2 = Time point 2, T3 = Time point 3, UPD = Updating, VPA = Vigorous physical activity. ***$p < .001$, ** $p < .01$,* $p < .05$.

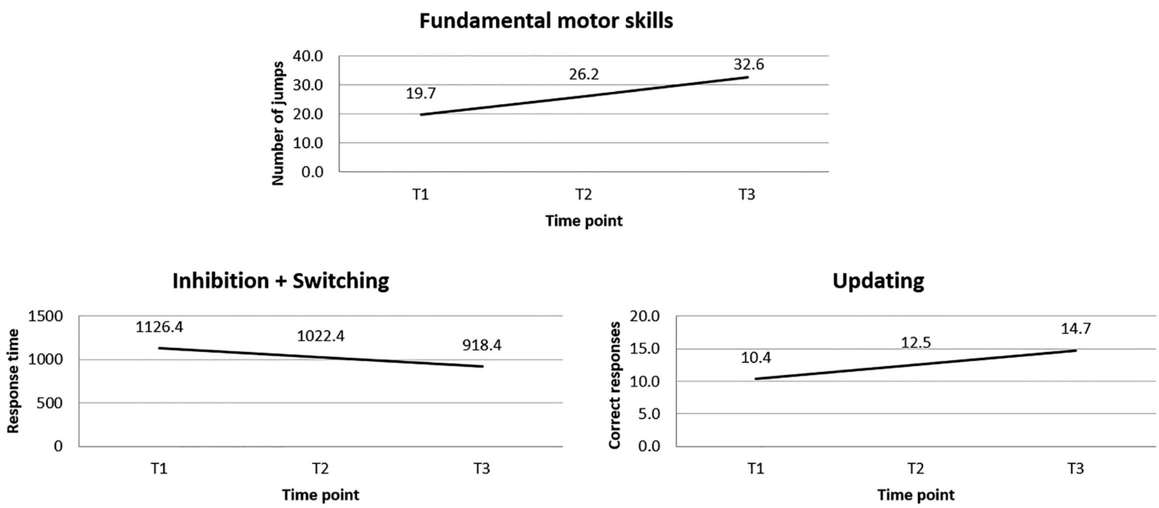

Fig. 2. The linear growth in fundamental motor skills, inhibition + switching and updating over three time points.

Table 4
Descriptive statistics from linear growth model for fundamental motor skills and executive functions.

	Mean	Variance
Intercept fundamental motor skills T1	19.66***	70.214***
Intercept Inhibition+switching T1	11.27***	5.67***
Intercept Updating T1	10.37***	15.46***
Slope fundamental motor skills T1-T3	6.49***	10.38**
Slope Inhibition+switching T1-T3	−1.04***	0.28**
Slope Updating T1-T3	2.18***	2.74*

Note. Intercept = Level at T1, Slope = Change between T1 and T3. *** $p < .001$, ** $p < .01$,* $p < .05$.

All three models testing the different physical activity intensity levels fitted data well. However, there were no statistically significant associations of moderate or moderate-to-vigorous physical activity with fundamental motor skills and executive functions. Therefore, a model with vigorous physical activity as a predictor was chosen to be the final model. The fit indices showed a good model fit for this model with the data: $\chi2$ (26) = 40.061, p = .0385, CFI = .983, TLI = .964, RMSEA = .041, SRMR = .031. The model explained 47 % of the variance in the early numeracy (Fig. 4).

The model showed that higher level of vigorous physical activity at T1 was related to slower response time and thus weaker performance in inhibition+switching. There were no statistically significant relations between vigorous physical activity, fundamental motor skills and updating.

3.4. *The relations of fundamental motor skills and executive functions to early numeracy (RQ4)*

We found that better performance in updating at the T1 and developmental rate of updating were positively associated with early numeracy. There were no relations between fundamental motor skills or inhibition+switching and early numeracy.

3.5. *The relations between physical activity and early numeracy through fundamental motor skills and early numeracy (RQ5)*

No indirect relations could be found in this model, as vigorous physical activity was associated only with the initial level of inhibition+switching, and inhibition+switching was not associated with early numeracy. rate of fundamental motor skills, inhibition+switching and updating.

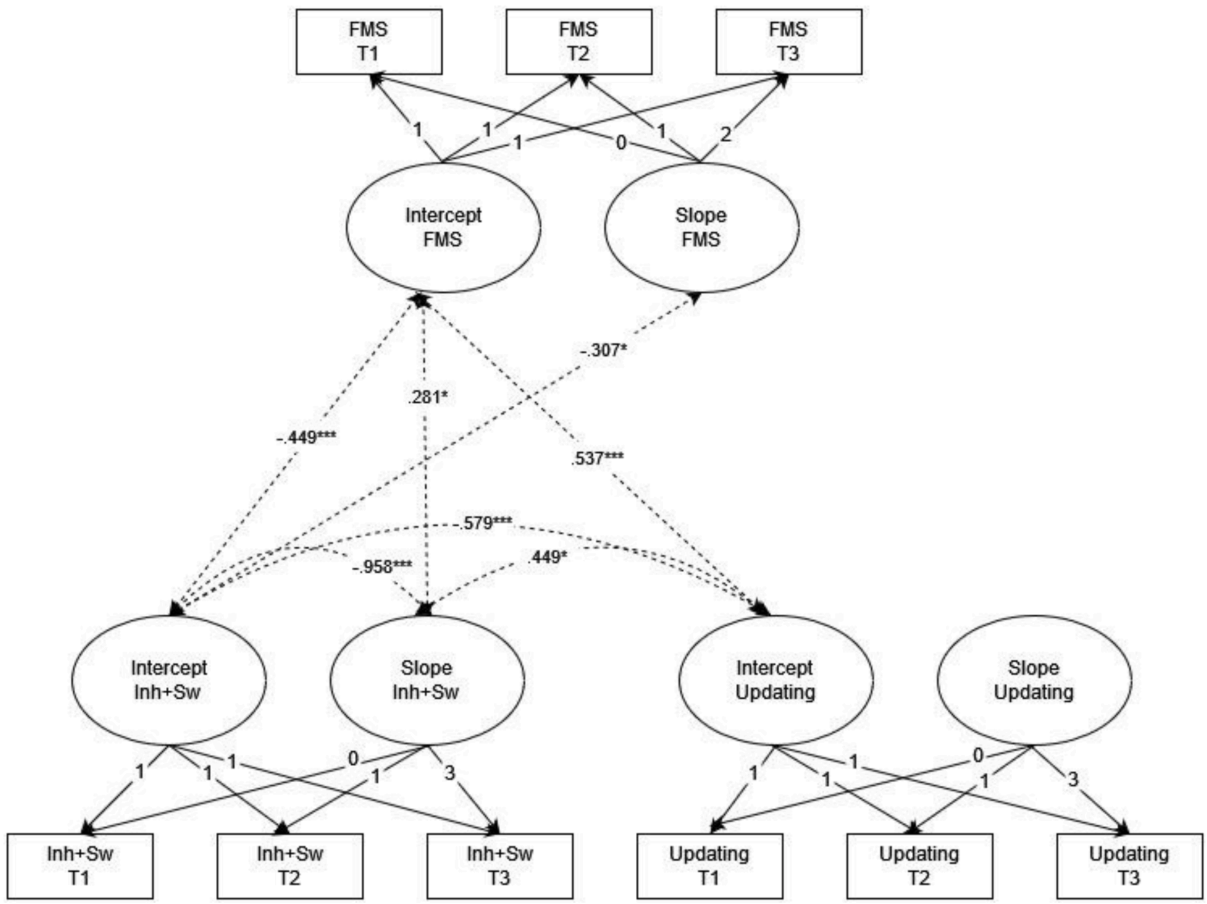

Fig. 3. The relations between intercept and slope of fundamental motor skills, inhibition + switching and updating.
Note. FMS = Fundamental motor skills, Inh+Sw = Inhibition and Switching, T1 = Time point 1, T2 = Time point 2, T3 = Time point 3. Only significant paths depicted.

4. Discussion

In this study, we examined the developmental associations of fundamental motor skills and executive functions, and how the development of these factors is related to early numeracy. We also examined whether physical activity predicts the development of fundamental motor skills, executive functions, and through them early numeracy. There were four main findings in the present study. First, we found that children with better fundamental motor skills at T1 developed slower in inhibition and switching. Second, children with better inhibition and switching ability at the T1 showed faster development in fundamental motor skills. These findings were in line with our hypothesis (H2) that fundamental motor skills and executive functions are developmentally related. However, contrary to our hypotheses, the relations were not only positive and growths of these factors were not related. Third, partly confirming our hypothesis (H4.2) updating at T1 and the developmental rate of updating predicted early numeracy performance at T3. In contrast to our expectations, there were no relations between inhibition and switching or fundamental motor skills (4.1) and early numeracy. Fourth, contrary to our hypothesis there were no positive relations of physical activity to level and change in fundamental motor skills (H3.1) or change in executive functions (H3.2). Instead, we found that children spending more time in vigorous physical activity at the T1 had a weaker initial level of inhibition and switching.

In addition to our main findings, as we expected (H1) children developed statistically significantly in fundamental motor skills and executive functions, and there were significant individual differences in the development. Contrary to our hypothesis, indirect associations between vigorous physical activity and early numeracy through fundamental motor skills and executive functions were not found (H5).

Our first main finding was that children who had better initial fundamental motor skills developed slower in inhibition/switching. This finding is contrary to previous evidence on positive cross-sectional [24,25] and longitudinal [28,29] associations between fundamental motor skills and executive functions in preschoolers. However, in these studies the relation between initial performance level and the developmental rate was not investigated. Development of inhibition and switching might explain our finding. Our results showed that children who had weaker initial inhibition and switching also had weaker fundamental motor skills and these children developed faster in inhibition and switching. Thus, the explanation for our finding of a negative relation between fundamental motor skills and developmental rate of inhibition and switching might be that children who have weaker fundamental motor skills also have weaker inhibition and switching ability and therefore have more room to develop in inhibition and switching during preschool. This is supported by our finding that also children with weaker initial updating developed faster in inhibition and switching indicating that some children developed later particularly in inhibition and switching and caught up their peers during preschool. Executive functions improve rapidly during preschool together with the development of prefrontal cortex [1] and our results may reflect differences in the developmental phase between children.

Our second main finding suggests that better inhibition and switching drives faster development in fundamental motor skills. A few studies have examined how executive functions predict fundamental motor skills. In one previous study, Peyre et al. [72] found that symptoms of inattention at age three years were negatively associated with motor skills development during preschool years (to 5–6 years). In turn, Zysset

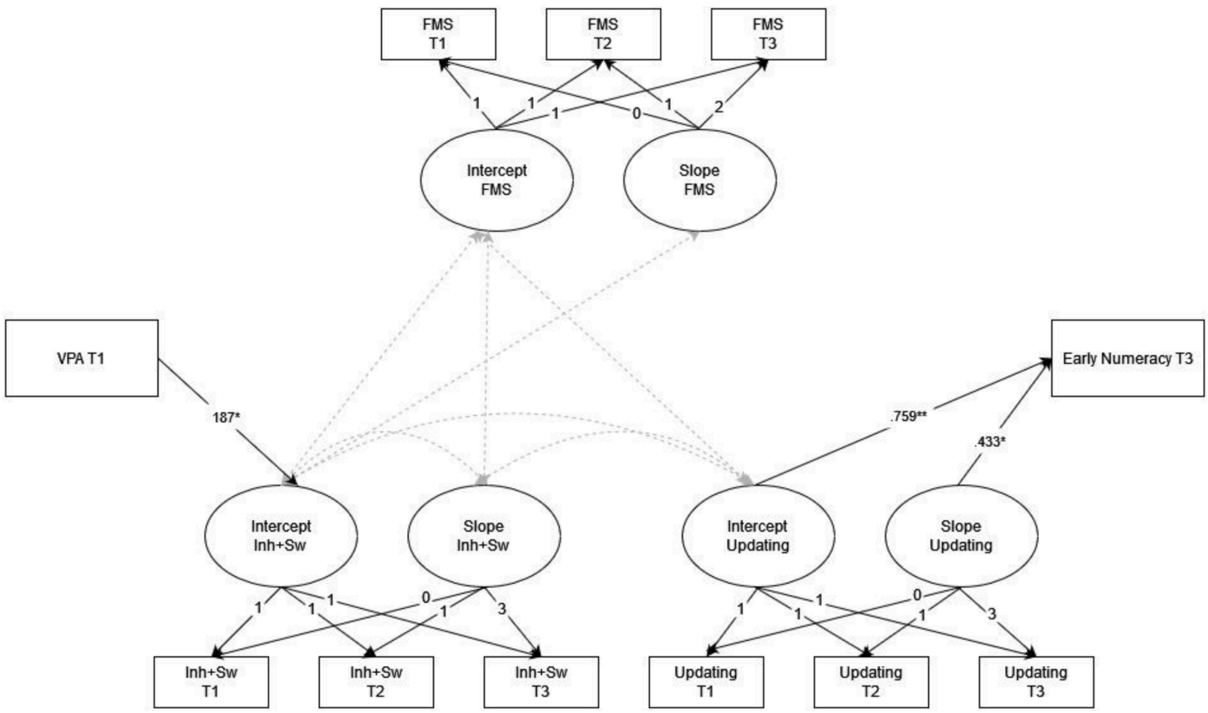

Fig. 4. The statistically significant paths between vigorous physical activity, fundamental motor skills, executive functions and early numeracy.
Note. FMS = Fundamental motor skills, Inh+Sw = Inhibition and Switching, VPA = Vigorous physical activity, T1 = Time point 1, T2 = Time point 2, T3 = Time point 3. Only significant paths depicted. The black solid lines depict the significant relations from vigorous physical activity at T1 to fundamental motor skills and executive functions and from fundamental motor skills and executive functions to early numeracy at T3. Gray dashed lines depict relations between fundamental motor skills and executive functions that are presented in more detail in Fig. 3.

and colleagues [73] found that motor skills predict cognitive functioning over one year, but not vice versa in 3–5-years old preschoolers. However, the rate of development was not examined in these studies. Many forms of physical activities that require fundamental motor skills are also cognitively engaging. Therefore, our findings may be explained through the importance of executive functions for performing complex motor tasks as a motor action plan must be created, monitored, and modified in relation to the demands of the motor task [39]. In addition, the ability to inhibit irrelevant information helps children to focus on the motor task, and the ability to switch is important for modifying the action plan. This may support children functioning in situations that require motor skills and thereby affect development of fundamental motor skills.

Our first two main findings at least partly support brain level evidence that fundamental motor skills and executive functions are developmentally interrelated [22]. However, our findings suggest that inhibition and switching drive the development of fundamental motor skills, but not vice versa. In addition, an improvement in one factor was not found to be related to an improvement in the other factor. Both fundamental motor skills and executive functions are rapidly developing during preschool age, influenced by naturally occurring development, environmental factors and experiences [1,13]. Our results suggest the complex developmental relations of these factors during preschool age. To the best of our knowledge, this was the first study to investigate the relations in developmental rates between fundamental motor skills and executive functions in preschoolers. A vast majority of studies among preschoolers have been based on the assumption that better motor skills predict better executive functions. Therefore, the developmental dynamics of these factors need to be further studied in the future.

The third main finding was that children who had better updating at T1, and who developed faster in updating, had better early numeracy at T3 highlighting the importance of specifically updating component of executive functions for early numeracy. The important predictive role of updating for early numeracy have been found in several previous studies in 5–6 [74–76], and 4-year-old children [37]. Our findings add to previous evidence that in addition to earlier performance level, the rate of development of updating also predicts early numeracy in 4–6 years old children. Updating is beneficial for early numeracy as it helps in storing and recalling relevant information for the task, and remembering the instructions of tasks [33]. Our finding that updating, but not inhibition and switching, is a predictor for early numeracy is in line with previous studies reporting that when updating, inhibition and switching are investigated together, updating is unique predictor for early numeracy [75,77]. The one explanation for this may be the requirements of updating in inhibition and switching tasks (maintaining representations of the inhibition and shifting task requirements, and of the sets between which shifting is necessary) resulting in updating explaining the largest proportion of the individual differences in EN [77]. This may also be explained through how inhibition and switching, and EN were measured. Response times were used to measure inhibition and switching, whereas early numeracy was measured by correct answers, and not by how quickly children can solve the task, leading to the low demands of inhibition in early numeracy tasks [78]. In addition, inhibition tasks also tested how children can cope with visual distractors, while in early numeracy task there was not that kind of interference, resulting in a mismatch between the measures [78].

Our fourth main finding was that children who spend more time in vigorous physical activity at T1 showed weaker performance in inhibition+switching at T1. This is in line with previous cross-sectional studies reporting negative associations between moderate-to-vigorous and executive functions [24,49]. The mechanism behind this negative association is not clear. One proposed explanation for this negative relation is hyperactive impulsive behavior, which is linked to weaker executive functions and may be related to a greater amount of physical activity [49]. However, based on the present study, we are not able to specify the explanation for the found relation. Vigorous physical activity has been found to positively predict switching in one previous longitudinal study in preschoolers [42]. However, there were no relations between vigorous physical activity and developmental rate in switching in the present study. Therefore, more studies are needed to clarify the longitudinal associations between physical activity and executive functions.

Overall, our findings indicate that the developmental dynamics between the physical activity, fundamental motor skills, executive functions and early numeracy is a complex and yet not well-known equation. We were able to demonstrate that in young children executive functions (inhibition and switching) supported the development of fundamental motor skills, and that executive functions (especially updating) is relevant for early numeracy development. We were not able to show a simple and straightforward developmental line which would go through from physical activity, fundamental motor skills, executive functions to early numeracy learning. More studies are needed to understand this complex developmental dynamics of these factors.

There are some limitations that should be taken into consideration when interpreting the results of the present study. First, due to practical reasons, only one task was used to measure the fundamental motor skills, and components of executive functions. Therefore, we could not use latent variables as factor indicators for the growth models that would have provided more pure measurements for these factors as task specific characteristics would have been filtered out. Second, children with a relatively wide age range was studied together masking possible developmental differences between children of different ages. Third, the time between T1 to T2 was only a half year for executive functions as it was one year for fundamental motor skills. This may have an effect on the results of developmental relations between fundamental motor skills and executive functions as the followed time of development was different. However, the time difference was not large and it was taken into account in the growth models. In addition, there was individual variation in the time between measurements, which may have had some effect on the results.

5. Conclusions

Findings indicate that the ability to inhibit and switch supports the development of fundamental motor skills, and the development of updating in particular seems to be an important predictor for early numeracy in preschool-age.

CRediT authorship contribution statement

Anssi Vanhala: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Anna Widlund:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Johan Korhonen:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Eero A. Haapala:** Conceptualization, Writing – review & editing. **Arja Sääkslahti:** Conceptualization, Writing – review & editing. **Pirjo Aunio:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

none

Acknowledgments

The authors thank all the families, children and the preschools for participating in the study, and everyone who participated in collecting the data.

Disclosure of interest

The authors report no conflict of interest

Funding details

This work was supported by The Ministry of Education and Culture [grant number OKM/42/626/2019]; and Cultural Foundation [Huhtamäen rahasto 2019, no grant number available].

Appendices

Appendix A

The coefficients and p-values for each path between level and slope of fundamental motor skills and executive functions.

	FMS$_{intercep}$	FMS$_{slope}$	Inh+Sw$_{intercept}$	Inh+Sw$_{slope}$	Updating$_{intercept}$	Updating$_{slope}$						
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
FMS$_{intercep}$	–	–										
FMS$_{slope}$	−.128	.398	–	–								
Inh+Sw$_{intercept}$	−.449	<.001	−.307	.012	–	–						
Inh+Sw$_{slope}$	.281	.028	.273	.123	−.958	<.001	–	–				
Updating$_{intercept}$	.537	<.001	.037	.773	−.579	<.001	.449	.015	–	–		
Updating$_{slope}$	.092	.344	−.087	.497	.001	.992	−.146	.392	.020	.913	–	–

Note. FMS = Fundamental motor skills, Inh+Sw = Inhibition and Switching. Significant paths are in bold.

Appendix B

The coefficients and p-values for each path of level and slope fundamental motor skills, executive functions to vigorous physical activity at T1 and early numeracy at T3.

	VPA T1		EN T3	
	β	p	β	p
FMS$_{intercep}$	.116	.130	−.002	.994
FMS$_{slope}$	.083	.437	−.045	.804
Inh+Sw$_{intercept}$	.187	.045	.931	.457
Inh+Sw$_{slope}$	−.315	.054	.808	.452

(*continued on next page*)

(*continued*)

	VPA T1		EN T3	
	β	p	β	p
$Updating_{intercept}$	.031	.766	.759	.001
$Updating_{slope}$	−.152	.142	.433	.035

Note. EN T3 = Early numeracy at time point three, FMS = Fundamental motor skills, Inh+Sw = Inhibition and Switching, VPA T1 = Vigorous physical activity at time point one. Significant paths are in bold.

References

[1] N. Garon, S.E. Bryson, I.M. Smith, Executive function in preschoolers: a review using an integrative framework, Psychol. Bull. 134 (1) (2008) 31–60, https://doi.org/10.1037/0033-2909.134.1.31.
[2] C.E. Cameron, L.L. Brock, W.M. Murrah, L.H. Bell, S.L. Worzalla, D. Grissmer, F. J. Morrison, Fine motor skills and executive function both contribute to kindergarten achievement: fine motor and kindergarten achievement, Child Dev. 83 (4) (2012) 1229–1244, https://doi.org/10.1111/j.1467-8624.2012.01768.x.
[3] S.A. Schmitt, G.J. Geldhof, D.J. Purpura, R. Duncan, M.M. McClelland, Examining the relations between executive function, math, and literacy during the transition to kindergarten: a multi-analytic approach, J. Educ. Psychol. 109 (8) (2017) 1120–1140, https://doi.org/10.1037/edu0000193.
[4] P.S. Tandon, A. Tovar, A.T. Jayasuriya, E. Welker, D.J. Schober, K. Copeland, D. A. Dev, A.L. Murriel, D. Amso, D.S. Ward, The relationship between physical activity and diet and young children's cognitive development: a systematic review, Prev. Med. Rep. 3 (2016) 379–390, https://doi.org/10.1016/j.pmedr.2016.04.003.
[5] M.T. Willoughby, K. Hudson, Contributions of motor skill development and physical activity to the ontogeny of executive function skills in early childhood, Dev. Rev. 70 (2023) 101102, https://doi.org/10.1016/j.dr.2023.101102.
[6] K.N. Hudson, H.M. Ballou, M.T. Willoughby, Short report: improving motor competence skills in early childhood has corollary benefits for executive function and numeracy skills, Dev. Sci. 24 (4) (2021), https://doi.org/10.1111/desc.13071 e13071-n/a.
[7] P. Tucker, The physical activity levels of preschool-aged children: a systematic review, Early Child. Res. Q. 23 (4) (2008) 547–558, https://doi.org/10.1016/j.ecresq.2008.08.005.
[8] T. Hinkley, J. Salmon, A.D. Okely, D. Crawford, K. Hesketh, Preschoolers' physical activity, screen time, and compliance with recommendations, Med. Sci. Sports . Exercise 44 (3) (2012) 458–465, https://doi.org/10.1249/MSS.0b013e318233763b.
[9] V.J. Poitras, C.E. Gray, X. Janssen, S. Aubert, V. Carson, G. Faulkner, G.S. Goldfield, J.J. Reilly, M. Sampson, M.S. Tremblay, Systematic review of the relationships between sedentary behaviour and health indicators in the early years (0–4 years), BMC Public Health 17 (5) (2017) 868, https://doi.org/10.1186/s12889-017-4849-8.
[10] F. Bardid, J. Rudd, M. Lenoir, R. Polman, L. Barnett, Cross-cultural comparison of motor competence in children from Australia and Belgium, Front. Psychol. 6 (2015). https://www.frontiersin.org/articles/10.3389/fpsyg.2015.00964.
[11] V. Carson, N. Kuzik, S. Hunter, S.A. Wiebe, J.C. Spence, A. Friedman, M. S. Tremblay, L.G. Slater, T. Hinkley, Systematic review of sedentary behavior and cognitive development in early childhood, Prev. Med. 78 (2015) 115–122, https://doi.org/10.1016/j.ypmed.2015.07.016.
[12] D.F. Stodden, C. Pesce, N. Zarrett, P. Tomporowski, T.D. Ben-Soussan, A. Brian, T. C. Abrams, M.D. Weist, Holistic functioning from a developmental perspective: a new synthesis with a focus on a multi-tiered system support structure, Clin. Child Fam. Psychol. Rev. 26 (2) (2023) 343–361, https://doi.org/10.1007/s10567-023-00428-5.
[13] W. Cools, K.D. Martelaer, C. Samaey, C. Andries, Movement skill assessment of typically developing preschool children: a review of seven movement skill assessment tools, J. Sports Sci. Med. 8 (2) (2009) 154–168.
[14] A. Miyake, N.P. Friedman, M.J. Emerson, A.H. Witzki, A. Howerter, T.D. Wager, The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis, Cogn. Psychol. 41 (1) (2000) 49–100, https://doi.org/10.1006/cogp.1999.0734.
[15] J.E. Clark, J Metcalfe, The mountain of motor development: a metaphor, in: Motor development: Research and Reviews, 2, 2002, pp. 163–190.
[16] S.W. Logan, S.M. Ross, K. Chee, D.F. Stodden, L.E. Robinson, Fundamental motor skills: a systematic review of terminology, J. Sports Sci. 36 (7) (2018) 781–796, https://doi.org/10.1080/02640414.2017.1340660.
[17] Gallahue, D.L., Goodway, J., & Ozmun, J.C. (2012). Understanding Motor development : infants, children, adolescents, Adults /David L. Gallahue, John C. Ozmun, Jackie D. Goodway. (7th ed.). McGraw-Hill.
[18] C.M. Roebers, M. Kauer, Motor and cognitive control in a normative sample of 7-year-olds, Dev. Sci. 12 (1) (2009) 175–181, https://doi.org/10.1111/j.1467-7687.2008.00755.x.
[19] R. Wassenberg, F.J.M. Feron, A.G.H. Kessels, J.G.M. Hendriksen, A.C. Kalff, M. Kroes, P.P.M. Hurks, M. Beeren, J. Jolles, J.S.H. Vles, Relation Between cognitive and motor performance in 5- to 6-year-old children: results from a large-scale cross-sectional study, Child Dev. 76 (5) (2005) 1092–1103, https://doi.org/10.1111/j.1467-8624.2005.00899.x.
[20] K.E. Adolph, J.M. Franchak, The development of motor behavior, Wiley Interdiscip. Rev. Cogn. Sci. 8 (1–2) (2017), https://doi.org/10.1002/wcs.1430 e1430–n/a.
[21] M. Abe, T. Hanakawa, Functional coupling underlying motor and cognitive functions of the dorsal premotor cortex, Behav. Brain Res. 198 (1) (2009) 13–23, https://doi.org/10.1016/j.bbr.2008.10.046.
[22] A. Diamond, Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex, Child Dev. 71 (1) (2000) 44–56, https://doi.org/10.1111/1467-8624.00117.
[23] P. Jylänki, T. Mbay, A. Hakkarainen, A. Sääkslahti, P. Aunio, The effects of motor skill and physical activity interventions on preschoolers' cognitive and academic skills: a systematic review, Prev. Med. 155 (2022) 106948, https://doi.org/10.1016/j.ypmed.2021.106948.
[24] K. Cook, S.J. Howard, G. Scerif, R. Twine, K. Kahn, S.A. Norris, C.E. Draper, Associations of physical activity and gross motor skills with executive function in preschool children from low-income South African settings, Dev. Sci. 22 (5) (2019), https://doi.org/10.1111/desc.12820 e12820–n/a.
[25] A. Vanhala, E.A. Haapala, A. Sääkslahti, A. Hakkarainen, A. Widlund, P. Aunio, Associations between physical activity, motor skills, executive functions and early numeracy in preschoolers, Eur. J. Sport Sci. 23 (7) (2023) 1385–1393, https://doi.org/10.1080/17461391.2022.2092777.
[26] V. Gashaj, N. Oberer, F.W. Mast, C.M. Roebers, Individual differences in basic numerical skills: the role of executive functions and motor skills, J. Exp. Child Psychol. 182 (2019) 187–195, https://doi.org/10.1016/j.jecp.2019.01.021.
[27] X. Han, M. Zhao, Z. Kong, J. Xie, Association between fundamental motor skills and executive function in preschool children: a cross-sectional study, Front. Psychol. 13 (2022) 978994, https://doi.org/10.3389/fpsyg.2022.978994.
[28] I. Niederer, S. Kriemler, J. Gut, T. Hartmann, C. Schindler, J. Barral, J.J. Puder, Relationship of aerobic fitness and motor skills with memory and attention in preschoolers (Ballabeina): a cross-sectional and longitudinal study, BMC Pediatr. 11 (1) (2011) 34, https://doi.org/10.1186/1471-2431-11-34.
[29] J.P. Piek, L. Dawson, L.M. Smith, N Gasson, The role of early fine and gross motor development on later motor and cognitive ability, Hum. Mov. Sci. 27 (5) (2008) 668–681, https://doi.org/10.1016/j.humov.2007.11.002.
[30] M. Willoughby, K. Hudson, Y. Hong, A. Wylie, Improvements in motor competence skills are associated with improvements in executive function and math problem-solving skills in early childhood, Dev. Psychol. 57 (9) (2021) 1463–1470, https://doi.org/10.1037/dev0001223.
[31] A.E. Zysset, T.H. Kakebeeke, N. Messerli-Bürgy, A.H. Meyer, K. Stülb, C.S. Leeger-Aschmann, E.A. Schmutz, A. Arhab, J.J. Puder, S. Kriemler, S. Munsch, O.G Jenni, Predictors of executive functions in preschoolers: findings from the SPLASHY study, Front. Psychol. 9 (2018) 2060, https://doi.org/10.3389/fpsyg.
[32] P. Aunio, M. Niemivirta, Predicting children's mathematical performance in grade one by early numeracy, Learn. Individ. Differ. 20 (5) (2010) 427–435, https://doi.org/10.1016/j.lindif.2010.06.003.
[33] R. Bull, K. Lee, Executive functioning and mathematics achievement, Child Dev. Perspect. 8 (1) (2014) 36–41, https://doi.org/10.1111/cdep.12059.
[34] P. Aunio, J. Korhonen, L. Ragpot, M. Törmänen, R. Mononen, E. Henning, Multi-factorial approach to early numeracy - the effects of cognitive skills, language factors and kindergarten attendance on early numeracy performance of South African first graders, Int. J. Educ. Res. 97 (2019) 65–76, https://doi.org/10.1016/j.ijer.2019.06.011.
[35] K.A. Espy, M.M. McDiarmid, M.F. Cwik, M.M. Stalets, A. Hamby, T.E. Senn, The contribution of executive functions to emergent mathematic skills in preschool children, Dev. Neuropsychol. 26 (1) (2004) 465–486, https://doi.org/10.1207/s15326942dn2601_6.
[36] C. Blair, R.P. Razza, Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten, Child Dev. 78 (2) (2007) 647–663, https://doi.org/10.1111/j.1467-8624.2007.01019.x.
[37] R. Bull, K.A. Espy, S.A. Wiebe, Short-term memory, working memory, and executive functioning in preschoolers: longitudinal predictors of mathematical achievement at age 7 years, Dev. Neuropsychol. 33 (3) (2008) 205–228, https://doi.org/10.1080/87565640801982312.
[38] E. de Waal, Fundamental movement skills and academic performance of 5- to 6-year-old preschoolers, Early Child. Educ. J. 47 (4) (2019) 455–464, https://doi.org/10.1007/s10643-019-00936-6.
[39] J. Best, Effects of physical activity on children's executive function: contributions of experimental research on aerobic exercise, Dev. Rev. 30 (4) (2010) 331–351, https://doi.org/10.1016/j.dr.2010.08.001.
[40] C.J. Caspersen, K.E. Powell, G.M. Christenson, Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research, Public Health Rep. 100 (2) (1985) 126–131.
[41] J. McNeill, S.J. Howard, S.A. Vella, R. Santos, D.P. Cliff, Physical activity and modified organized sport among preschool children: associations with cognitive

and psychosocial health, Ment Health Phys. Act 15 (2018) 45–52, https://doi.org/10.1016/j.mhpa.2018.07.001.
[42] J. McNeill, S.J. Howard, S.A. Vella, D.P. Cliff, Longitudinal associations of physical activity and modified organized sport participation with executive function and psychosocial health in preschoolers, J Sports Sci 38 (24) (2020) 2858–2865, https://doi.org/10.1080/02640414.2020.1803037.
[43] V. Carson, A.A. Rahman, S.A. Wiebe, Associations of subjectively and objectively measured sedentary behavior and physical activity with cognitive development in the early years, Ment. Health Phys. Act 13 (2017) 1–8, https://doi.org/10.1016/j.mhpa.2017.05.003.
[44] X. Luo, F. Herold, S. Ludyga, M. Gerber, K. Kamijo, M.B. Pontifex, C.H. Hillman, B. L. Alderman, N.G. Müller, A.F. Kramer, T. Ishihara, W. Song, L. Zou, Association of physical activity and fitness with executive function among preschoolers, Int. J. Clin. Health Psychol. 23 (4) (2023) 100400, https://doi.org/10.1016/j.ijchp.2023.100400.
[45] M.W. Voss, L.J. Carr, R. Clark, T. Weng, Revenge of the "sit" II: does lifestyle impact neuronal and cognitive health through distinct mechanisms associated with sedentary behavior and physical activity? Ment. Health Phys. Act 7 (1) (2014) 9–24, https://doi.org/10.1016/j.mhpa.2014.01.001.
[46] C.H. Hillman, K.I. Erickson, A.F. Kramer, Be smart, exercise your heart: exercise effects on brain and cognition, Nat. Rev. Neurosci. 9 (1) (2008) 58–65, https://doi.org/10.1038/nrn2298.
[47] V. Carson, S. Hunter, N. Kuzik, S.A. Wiebe, J.C. Spence, A. Friedman, M. S. Tremblay, L. Slater, T. Hinkley, Systematic review of physical activity and cognitive development in early childhood, J. Sci. Med. Sport 19 (7) (2016) 573–578, https://doi.org/10.1016/j.jsams.2015.07.011.
[48] C.W. St. Laurent, S. Burkart, C. Andre, R.M.C Spencer, Physical activity, fitness, school readiness, and Cognition in early childhood: a systematic review, J. Phys. Activ. Health 18 (2021) 1004–1013, https://doi.org/10.1123/jpah.2020-0844.
[49] W.A.C. Willoughby, A.C. Wylie, D.J. Catellier, Testing the association between physical activity and executive function skills in early childhood, Early Child. Res. Q. 44 (2018) 82–89, https://doi.org/10.1016/j.ecresq.2018.03.004.
[50] N. Zeng, M. Ayyub, H. Sun, X. Wen, P. Xiang, Z. Gao, Effects of physical activity on motor skills and cognitive development in early childhood: a systematic review, Biomed. Res. Int. (2017) 2760716, https://doi.org/10.1155/2017/2760716.
[51] J.E. Donnelly, C.H. Hillman, D. Castelli, J.L. Etnier, S. Lee, P. Tomporowski, K. Lambourne, A.N. Szabo-Reed, Physical activity, fitness, cognitive function, and academic achievement in children: a systematic review, Med. Sci. Sports Exerc. 48 (6) (2016) 1197–1222, https://doi.org/10.1249/MSS.0000000000000901.
[52] P.D. Tomporowski, B. McCullick, D.M. Pendleton, C. Pesce, Exercise and children's cognition: the role of exercise characteristics and a place for metacognition, J. Sport Health Sci. 4 (1) (2015) 47–55, https://doi.org/10.1016/j.jshs.2014.09.003.
[53] D.F. Stodden, J.D. Goodway, S.J. Langendorfer, M.A. Roberton, M.E. Rudisill, C. Garcia, L.E. Garcia, A developmental perspective on the role of motor skill competence in physical activity: an emergent relationship, Quest (Natl. Assoc.r Kinesiol. Higher Educ.) 60 (2) (2008) 290–306, https://doi.org/10.1080/00336297.2008.10483582.
[54] F. Bürgi, U. Meyer, U. Granacher, C. Schindler, P. Marques-VIdal, S. Kriemler, J. Puder, Relationship of physical activity with motor skills, aerobic fitness and body fat in preschool children: a cross-sectional and longitudinal study (Ballabeina), Int. J. Obes. 35 (7) (2011) 937–944, https://doi.org/10.1038/ijo.2011.54.
[55] A.K.O. Nilsen, S.A. Anderssen, K. Johannessen, K.N. Aadland, E. Ylvisaaker, J. M. Loftesnes, E. Aadland, Bi-directional prospective associations between objectively measured physical activity and fundamental motor skills in children: a two-year follow-up, Int. J. Behav. Nutr. Phys. Act 17 (1) (2020) 1, https://doi.org/10.1186/s12966-019-0902-6.
[56] D.R. Becker, M.M. McClelland, P. Loprinzi, S.G Trost, Physical activity, self-regulation, and early academic achievement in preschool children, Early Educ. Dev. 25 (1) (2014) 56–70, https://doi.org/10.1080/10409289.2013.780505.
[57] D.W. Esliger, J.L. Copeland, J.D. Barnes, M.S. Tremblay, Standardizing and optimazing the use of accelerometer data for free-living physical activity monitoring, J. Phys. Activ. Health 3 (2005) 366–383, https://doi.org/10.1123/jpah.2.3.366.
[58] D.D. Bingham, S. Costa, S.A. Clemes, A.C. Routen, H.J. Moore, S.E. Barber, Accelerometer data requirements for reliable estimation of habitual physical activity and sedentary time of children during the early years - a worked example following a stepped approach, J. Sports Sci. 34 (20) (2016) 2005–2010, https://doi.org/10.1080/02640414.2016.1149605.
[59] R.R. Pate, M.J. Almeida, K.L. McIver, K.A. Pfeiffer, M. Dowda, Validation and calibration of an accelerometer in preschool children, Obes. (Silver Spring) 14 (11) (2006) 2000–2006, https://doi.org/10.1038/oby.2006.234.
[60] D. Jones, A. Innerd, E.L. Giles, L.B. Azevedo, Association between fundamental motor skills and physical activity in the early years: a systematic review and meta-analysis, J. Sport Health Sci. 9 (6) (2020) 542–552, https://doi.org/10.1016/j.jshs.2020.03.001.
[61] Kiphard, E.J., & Schilling, F. (2007). The Körperkoordinationstest für kinder (KTK). Weinham: beltz Test.
[62] S. Iivonen, A. Kaarina Sääkslahti, A. Laukkanen, A review of studies using the Körperkoordinationstest für Kinder (KTK), Eur. J. Adapted Phys. Activ. 8 (2) (2015) 18–36, https://doi.org/10.5507/euj.2015.006.
[63] K. Lee, R. Bull, R.M.H. Ho, Developmental changes in executive functioning, Child Dev. 84 (6) (2013) 1933–1953, https://doi.org/10.1111/cdev.12096.
[64] A. Vanhala, K. Lee, J. Korhonen, P. Aunio, Dimensionality of executive functions and processing speed in preschoolers, Learn. Individ. Differ. 107 (2023) 102361. https://doi.org/10.1016/j.lindif.2023.102361.
[65] M.C. Davidson, D. Amso, L.C. Anderson, A. Diamond, Development of cognitive control and executive functions from 4 to 13 years: evidence from manipulations of memory, inhibition, and task switching, Neuropsychologia 44 (2006) 2037–2078.
[66] J.E.H. Van Luit, B.A.M. Van de Rijt, P. Aunio, Early numeracy test (lukukäsitetesti). Psykologien kustannus, [in Finnish] (2006).
[67] R.J.A. Little, A Test of Missing Completely at Random for Multivariate Data with Missing Values, J Am Stat Assoc 83 (404) (1988) 1198–1202, https://doi.org/10.1080/01621459.1988.10478722.
[68] F.F. Chen, Sensitivity of goodness of fit indexes to lack of measurement invariance, Struct. Eq. Model. 14 (3) (2007) 464–504, https://doi.org/10.1080/10705510701301834.
[69] L. Hu, P.M. Bentler, Cutoff criteria for fit indexes in covariance structure analysis: conventional criteria versus new alternatives, Struct. Eq. Model. 6 (1) (1999) 1–55, https://doi.org/10.1080/10705519909540118.
[70] H.W. Marsh, K.-T. Hau, Z. Wen, In search of golden rules: comment on hypothesis-testing approaches to setting cutoff values for fit indexes and dangers in overgeneralizing Hu and Bentler's (1999) findings, Struct. Eq. Model. 11 (3) (2004) 320–341, https://doi.org/10.1207/s15328007sem1103_2.
[71] B.O. Muthen, L.K. Muthen, Mplus (version 8.6), Muthen & Muthen, Los Angeles, 1998–2021.
[72] H. Peyre, J.-M. Albaret, J.Y. Bernard, N. Hoertel, M. Melchior, A. Forhan, M. Taine, B. Heude, M. De Agostini, C. Galéra, F. Ramus, Developmental trajectories of motor skills during the preschool period, Eur. Child Adolesc. Psychiatry 28 (11) (2019) 1461–1474, https://doi.org/10.1007/s00787-019-01311-x.
[73] A.E. Zysset, T.H. Kakebeeke, N. Messerli-Bürgy, A.H. Meyer, K. Stülb, C.S. Leeger-Aschmann, E.A. Schmutz, A. Arhab, J.J. Puder, S. Kriemler, S. Munsch, O.G. Jenni, Stability and prediction of motor performance and cognitive functioning in preschoolers: a latent variable approach, Infant. Child Dev. (5) (2020) 29, https://doi.org/10.1002/icd.218.
[74] M.E. Kolkman, H.J.A. Hoijtink, E.H. Kroesbergen, P.P.M. Leseman, The role of executive functions in numerical magnitude skills, Learn Individ. Differ. 24 (2013) 145–151, https://doi.org/10.1016/j.lindif.2013.01.004.
[75] K. Lee, S.F. Ng, M.L. Pe, S.Y. Ang, M.N.A.M. Hasshim, R. Bull, The cognitive underpinnings of emerging mathematical skills: executive functioning, patterns, numeracy, and arithmetic: cognitive underpinnings, Br. J. Educ. Psychol. 82 (1) (2012) 82–99, https://doi.org/10.1111/j.2044-8279.2010.02016.x.
[76] S. Monette, M. Bigras, M.-C. Guay, The role of the executive functions in school achievement at the end of Grade 1, J Exp Child Psychol 109 (2) (2011) 158–173, https://doi.org/10.1016/j.jecp.2011.01.008.
[77] S.H.G. van der Ven, E.H. Kroesbergen, J. Boom, P.P.M. Leseman, The development of executive functions and early mathematics. A dynamic relationship, Br. J. Educ. Psychol. 82 (2012) 100–119, https://doi.org/10.1111/j.2044-8279.2011.02035.x.
[78] K. Lee, H.W. Lee, Inhibition and mathematical performance: poorly correlated, poorly measured, or poorly matched? Child Dev. Perspect. 13 (1) (2019) 28–33, https://doi.org/10.1111/cdep.12304.