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Associations between physical activity, motor skills, executive functions and early numeracy in preschoolers

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ABSTRACT

We investigated direct and indirect cross-sectional associations of physical activity, fundamental motor skills, executive functions, and early numeracy in preschoolers. The participants were 214 preschoolers aged three to five years. Time spent in moderate and vigorous physical activity was measured by hip-worn accelerometers and fundamental motor skills using the tasks assessing locomotor, object control, and stability skills. Inhibition/switching and working memory/updating, as components of executive functions, were assessed by computerised tests and a standardised test was used to assess early numeracy. Path analyses were used to examine direct and indirect associations between the constructs. Our results showed that stability skills were indirectly positively associated with early numeracy through inhibition/switching ($\beta = 0.07$, $p < 0.05$, 95% CI [0.02, 0.14]) and locomotor skills through working memory/updating ($\beta = 0.13$, $p = 0.001$, 95% CI [0.06, 0.20]). Vigorous physical activity was positively associated with early numeracy through locomotor skills and working memory/updating ($\beta = 0.04$, $p = 0.01$, 95% CI [0.01, 0.07]) and negatively associated with early numeracy through inhibition/switching ($\beta = -0.06$, $p < 0.05$, 95% CI [−0.11, −0.02]).

Highlights

- Locomotor skills are positively associated with early numeracy through working memory/updating.
- Stability skills are positively associated with early numeracy through inhibition/switching.
- Vigorous physical activity is indirectly associated with early numeracy: Positively through locomotor skills and working memory/updating and negatively through inhibition/switching.

KEYWORDS
Exercise; Cognition; Academic skills; Early childhood

1. Introduction

Early numeracy (EN; i.e. numerical relational and counting skills) is an important predictor for later mathematical and academic performance (Aunio & Niemivirta, 2010) and it is positively associated with mathematical skills throughout schooling (Duncan et al., 2007). Furthermore, executive functions (EF: higher-order cognitive processes typically divided into three main components: inhibition (ability to inhibit dominant, automatic or prepotent responses), updating (monitor incoming information, and refresh and maintain information in mind) and switching (ability to move between multiple tasks, operations, or mental sets)) (Miyake et al., 2000) have been found to contribute to the development of EN (Schmitt, Geldhof, Purpura, Duncan, & McClelland, 2017). In addition, weaker EF have been associated with difficulties to learn EN in pre-school-aged children (Clark, Sheffield, Wiebe, & Espy, 2013). Therefore it is important to identify factors that may influence the development of EN and EF in early childhood.

Physical activity (PA) (Best, 2010) and fundamental motor skills (FMS) (Hudson, Ballou, & Willoughby, 2020) are potential factors associated with EF and EN in children. These quantitative (PA) and qualitative (FMS) aspects of exercise may contribute to cognitive skills through different underlying mechanisms (Pesce, 2012). PA is defined as bodily movement produced by skeletal muscles that result in energy expenditure (Caspersen, Powell, & Christenson, 1985) and has been

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argued to directly affect executive functions through physiological changes in the brain (e.g. increased cerebral blood flow) and cognitive demands of physical activities (e.g. group activities) (Best, 2010). FMS are crucial for everyday life in children and they are defined as building blocks for complex movements required to participate in context-specific physical activities (e.g. games). FMS are divided into locomotor (e.g. running, jumping), object control (e.g. throwing, catching), and stability skills (ability to control the body) (Logan, Ross, Chee, Stodden, & Robinson, 2018). FMS have been connected to cognitive skills through cognitive engagement required to execute complex motor movements, and the co-activation in the brain areas important for complex motor and cognitive functions cerebellum and the prefrontal cortex (Best, 2010). However, most pre-school children do not meet the PA recommendations and spend most of their daily time in sedentary activities (Soini et al., 2014), while secular declines in FMS have also been reported (Roth et al., 2010). Furthermore, PA has been suggested to support the development of FMS (Stodden et al., 2008) and moderate-to-vigorous physical activity (MVPA) has been associated with FMS in early years (Nilsen et al., 2020). Findings from the early intervention studies have detected beneficial effects of PA on both motor and cognitive development (Zeng et al., 2017). Therefore, FMS may mediate the associations of PA with EF and EN. Taken together, insufficient levels of PA and decreased FMS raises concerns about the effects of this trend on the development of cognitive and academic skills in children.

Early childhood is characterised by a rapid and parallel development of motor and cognitive skills (Stodden et al., 2008; Best & Miller, 2010). Improvements in FMS have been associated with increases in EF and EN in three- to five-year-old children (Hudson et al., 2020). However, recent cross-sectional studies have reported conflicting findings on the associations between FMS and EF in early childhood. Cook et al. (2019) reported that locomotor skills were positively associated with inhibition and working memory, while object control skills were only associated with inhibition. Moreover, they found no associations between shifting and locomotor or object control skills (Cook et al., 2019). Stability skills have been positively associated with EF including inhibition, shifting, and updating in children aged five to seven years (Oberer, Gashaj, & Roebers, 2017; Gashaj, Oberer, Mast, & Roebers, 2019). Stability skills have also been positively associated with working memory after a nine-month follow-up in preschoolers (Niederer et al., 2011).

To our knowledge, only one study has investigated the relationship between FMS and EN in early childhood. Gashaj et al. (2019) found that stability skills were related to non-symbolic magnitude comparison but not with symbolic number comparison or number line task (symbolic or non-symbolic) in children aged six to seven years.

There is preliminary evidence that EF benefits from PA in preschoolers, but findings have been inconsistent (St. Laurent, Burkart, Andre, & Spencer, 2021). Cross-sectional studies have shown positive, negative, and insignificant associations between MVPA and vigorous physical activity (VPA) and EF in preschoolers. McNeill, Howard, Vella, Santos, and Cliff (2018) found that VPA was positively associated with visual-spatial working memory. In turn, Willoughby, Wylie, and Catellier (2018) reported an inverse association of MVPA with EF performance including inhibitory control and working memory. Furthermore, whereas MVPA was not associated with inhibition or shifting, it was inversely associated with working memory in one previous study (Cook et al., 2019). McNeill and colleagues longitudinal study (McNeill, Howard, Vella, & Cliff, 2020) showed that baseline VPA and MVPA were positively associated with shifting, but not with inhibition or working memory performance assessed one year later.

Despite the evidence of the relation between PA and EF (Best, 2010) and the findings that EF are closely related to the development of EN (Clark et al., 2013), there are a few studies investigating the relationship between PA and EN in preschoolers. Becker, Mcclelland, Loprinzi, and Trost (2014) did not find statistically significant direct associations between MVPA during preschool outdoor play and EN. In addition to being strongly associated with mathematical skills (Clark et al., 2013), EF has been found to mediate the association of PA (Donnelly et al., 2016) and FMS (Schmidt et al., 2017) with mathematical skills in school-aged children. In early childhood, MVPA during pre-school outdoor play has been associated with EN through inhibition (Donnelly et al., 2016) and stability skills have been linked to EF and EN skills (Becker et al., 2014).

The evidence regarding the associations of PA and FMS with EF and EN in preschoolers is still lacking. Previous studies have investigated only some components of FMS (e.g. locomotor and object control, but not stability skills) (Cook et al., 2019) or EN (e.g. number line, magnitude comparison) (Gashaj et al., 2019) and there are no previous studies that have investigated all these factors together. Therefore, we examined direct and indirect associations of moderate physical activity (MPA) and VPA, and FMS (quantified as locomotor, object control, and stability skills) with EF (components of working memory/updating and inhibition/switching), and EN in preschoolers. First, we investigated direct associations between PA, FMS, EF, and EN. Second, we examined the mediating role of EF in the associations of PA and FMS with EN. Finally, we investigated the association of PA with EN through FMS and EF.

2. Methods

2.1. Study design and study population

This cross-sectional study was part of the Active Early Numeracy Study. Participants were recruited from 16 preschools in the metropolitan area of Finland in October 2019. Invitation letters were delivered to the parents of children ($n = 632$) born in 2015 and 2016 in these preschools and a total of 348 children agreed to participate in this study. Finally, data from 214 children (104 boys, 110 girls) aged three to five years ($M = 3.93$, $SD = 0.63$) with valid PA data were included in the analyses. Based on parental questionnaire ($n = 187$), 48% of the children participated in organised sports activities outside preschool hours.

Parents signed a consent form for their children to participate in the study. Children were informed that participation was voluntary. The University's ethics committee approved the study protocol.

2.2. Study protocol

Trained and qualified PhD students and research assistants performed all the assessments. The assessments were divided into four approximately 30-minute test sessions: 1) locomotor and object control skills, 2) stability skills, 3) working memory/updating and inhibition/switching, and 4) EN. FMS were assessed in groups of two or three children. Tests for EN and EF were performed with one child at a time in a separate quiet room. There was one test session per day for one child and tests were administered in a random order.

2.3. Measures

2.3.1. Physical activity

PA was measured using a waist-mounted lightweight Actigraph wGT3X-BT accelerometers (ActiGraph, Pensacola, FL, USA). The monitor was attached on 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 (Esliger, Copeland, Barnes, & Tremblay, 2005). Data were included in the analyses if the children had a minimum of 480 min of data on at least three days and at least one of those valid days was a weekend day (Bingham et al., 2016). Data were collected using 100 Hz sampling frequency and raw data were then reintegrated in 15s epochs using ActiLife software (version 6.13.4). The time spent in different intensity levels was defined using age-appropriate cut points: ≥ 1680 counts/min for MPA and ≥ 3368 counts/min for VPA (Pate, Almeida, McIver, Pfeiffer, & Dowda, 2006). To minimise the effect of wearing time, the percentage of time spent in moderate and vigorous-intensity levels in relation to wearing time was calculated and used in the analysis. In this study, we focused on MPA and VPA as previous studies have shown that these intensity levels have been found to be particularly beneficial for EF among preschoolers (McNeill et al., 2018, 2020).

2.3.2. Fundamental motor skills

Three components of FMS, namely locomotor, object control and stability skills were assessed. Locomotor and object control skills were measured with The Test of Gross Motor Development 3 (TGMD-3) (Ulrich, 2019). TGMD-3-test is a reliable and valid process-oriented tool suitable for children aged 3–11 years, assessing 13 different FMS through direct observation. The subtest assessing locomotor skills included six tasks (run, gallop, hop, skip, horizontal jump and slide) and object control skills included seven tasks (two-hand strike, one-hand forehand strike, one-hand stationary dribble, two-hand catch, kick, overhand throw, underhand throw). Each skill was assessed by examining three to five criteria. Scores were given from each criterion, one from passed and zero from failed attempt. Points from each criterion in both trials were summed to represent locomotor and object control skills (maximum being 46 and 54, respectively). In this sample, internal consistency was good for both locomotor ($\alpha = 0.88$) and object control skills ($\alpha = 0.86$). Sum scores for locomotor and object control skills were used in the analysis.

To measure stability skills, jumping sideways and balancing beam tasks from the Körperkoordinationstest für Kinder (Kiphard & Schilling, 2007), and one-leg stance from The Movement Assessment Battery for Children (M-ABC-2-test) (Petermann, 2009) were performed. In the jumping sideways 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. The number of the correct jumps in the two trials were summed as the total score of the task. In the balancing beam task, children walked backwards on beams with different widths (6, 4.5, 3 cm). Each beam was performed three times and the number of steps in total of nine trials were summed. Eight was the maximum number of the steps in each trial (max. 72 points). In the one-leg stance task children were instructed to stand on one leg for as long as possible. Maximum standing time in one-leg was 30 s. Two trials were performed on each leg. The longer standing time in seconds on each leg was summed as total time in one-leg stance. Stability skills displayed a good internal consistency ($\alpha = 0.82$).

2.3.3. Executive functions

EF were assessed by computer-based tests using the ePrime software. Two components of EF were assessed: Inhibition/switching were assessed using the Flanker task and working memory/updating using the pictorial updating task (Lee, Bull, & Ho, 2013). In the Flanker task, a row of five fish were presented on the screen and children were asked to identify the direction of the middle fish by pressing a key pointing in the same direction. The fish in the middle was facing in either the same (congruent trial) or different direction (incongruent trial) than all the other fish. There were 36 congruent and incongruent trials in the test. One point was given for each correctly answered trial. In the pictorial updating task, a varying number of animal pictures were shown one at a time on the computer screen. At the end of each trial, children were asked to remember a specified number (one to three) of animals that were presented last in the correct order. Children were instructed to select animals by pressing animal figures presented on the screen. One point was given for each animal recalled in the correct order. The sum scores for both EF measures were used in the analysis (maximum being 72 for the Flanker and 36 for the Pictorial updating).

2.3.4. Early numeracy

EN was measured using the Early Numeracy test (Van Luit, Van de Rijt, & Aunio, 2006), which included a total of 40 items measuring numerical relational (comparison, classification, correspondence, seriation) and counting (using number words, synchronous and shortened counting, resultative counting, and general knowledge of the numbers) skills. The administrator presented the questions, 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. The test showed good internal consistency in this sample ($\alpha = 0.90$). Sum scores in the Early Numeracy test were used in the analysis.

2.4. Statistical analysis

First, distribution, outliers, and missing values were examined. The Kolmogorov–Smirnov test showed that MPA and the jumping sideways task were normally distributed. The distribution of all other variables was skewed. Values one and a half times higher or lower than the interquartile range were treated as outliers using the Winsorizing method (Dixon, 1960). Little's MCAR test (Little, 1988) showed that values were missing completely at random ($p = 0.42$). Means and standard deviations were calculated for all subjects and separately for boys and girls. Independent samples t-test was conducted to compare gender differences in each variable. Descriptive statistics are presented in Table 1. The associations between PA, FMS, and EN were first analyzed in SPSS (Version 28, IBM corp., Armonk, NY, USA) by using bivariate correlations. Pearson's correlation coefficients were calculated for normally and Spearman's rank correlation coefficient for non-normally distributed variables (Table 2).

For the main analyses, age-controlled variables were constructed in SPSS by regressing test age of each test on test scores and by saving standardised residuals as a new variables. A variable for stability skills was constructed

Table 1. Descriptive statistics on physical activity, fundamental motor skills, executive functions and early numeracy.

Variable	Total	Boys	Girls				
	N	M (SD)	*n*	M (SD)	*n*	M (SD)	t-test
Physical activity							
Moderate activity (% of wearing time)	214	10.6 (2.3)	104	11.3 (2.2)	110	9.6 (2.2)	4.27***
Vigorous activity (% of wearing time)	214	4.2 (1.8)	104	4.5 (1.8)	110	4.0 (1.8)	1.71
Fundamental motors skills							
Locomotor skills (TGMD-test sum score)	188	17.5 (7.6)	91	15.9 (6.6)	97	19.0 (8.2)	−2.85**
object control skills (TGMD-test sum score)	188	16.0 (6.3)	91	17.3 (7.2)	97	14.9 (5.2)	2.59*
Jumping sideways (jumps)[a]	181	19.8 (8.5)	85	19.3 (9.2)	96	20.2 (8.0)	−0.75
One-leg stance (time in seconds)[a]	180	19.6 (16.4)	85	14.4 (13.0)	95	24.2 (17.8)	−4.25***
Balancing beam (steps)[a]	182	14.1 (9.7)	86	11.6 (8.1)	96	16.3 (10.5)	3.40**
Executive function							
Working memory (Pictorial updating task sum score)	138	10.6 (5.3)	67	10.0 (5.2)	71	11.2 (5.4)	−1.39
Inhibition/switching (Flanker task sum score)	139	55.1 (13.2)	68	53.4 (14.0)	71	56.7 (12.3)	−1.50
Early numeracy							
EN test (sum score)	201	12.5 (7.1)	96	11.6 (7.1)	105	13.4 (7.2)	−1.79

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, compared the values of boys and girls.
Abbreviation: M = Mean, SD = Standard deviation.
[a]Indicators assessing stability.

Table 2. Bivariate correlations between physical activity, fundamental motor skills, executive functions and early numeracy.

	MPA	VPA	LM	OC	JS	OLS	BB	WM/UP	IN/SW	EN
MPA	–									
VPA	0.64***	–								
LM	0.24**	0.33***	–							
OC	0.18*	0.19*	0.26***	–						
JS	0.05	0.21**	0.38***	0.26***	–					
OLS	−0.05	0.09	0.35***	0.06	0.31***	–				
BB	0.00	0.06	0.46***	0.08	0.43***	0.56***	–			
WM/UP	−0.02	0.13	0.34***	0.12	0.24*	0.02	0.27**	–		
IN/SW	−0.22*	−0.19*	0.13***	−0.03	0.22*	0.10	0.26**	0.23**	–	
EN	−0.00	0.05	0.20*	−0.20	0.23**	0.08	0.26***	0.44***	0.35***	–

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.
Abbreviation: BB = balancing beam, EN = early numeracy, IN/SW = inhibition/switching (The Flanker task), JS = jumping sideways, LM = locomotor skills, MPA = moderate physical activity, OC = object control skills, OLS = one leg stance, VPA = vigorous physical activity, WM/UP = working memory/updating (The Pictorial updating task).

by calculating the mean of standardised residuals for three stability tests. In the next step, direct and indirect associations of MPA and VPA with locomotor, object control and stability skills, working memory/updating, inhibition/switching and EN were analyzed using path analysis constructed using Mplus software version 8.3 (Muthén & Muthén, Los Angeles, CA, USA). Maximum likelihood estimator (ML) were used in the path analysis. The comparative Fit Index (CFI; cut-off values close to > 0.95), Tucker Lewis Index (TLI; cut-off values close to > 0.95), Root Mean Square Error of Approximation (RMSEA; cut-off values close to < 0.05) and Standardised Root Mean Square Residual (SRMR; cut-off values close to < 0.05) were as a criterion for good model fit (Hu & Bentler, 1999). First, according to our hypothetical model (see Figure 1) all direct paths between MPA, VPA, FMS, EF and EN were tested. However, we found that MPA was not significantly related to any other construct in the model, and therefore, in the next step, we specified our model to only include VPA. In the final phase of the analysis, only significant paths were specified in the model (Figure 2). The significance of indirect effects was tested by using bootstrap confidence intervals (95%) with 5000 bootstrap draws. The Wald chi-square test was used to test gender differences in the significant path coefficients.

3. Results

3.1. Direct associations between physical activity, motor skills, executive functions and early numeracy

First, direct associations of VPA, FMS, EF, and EN were investigated (Figure 2). The fit indices showed good

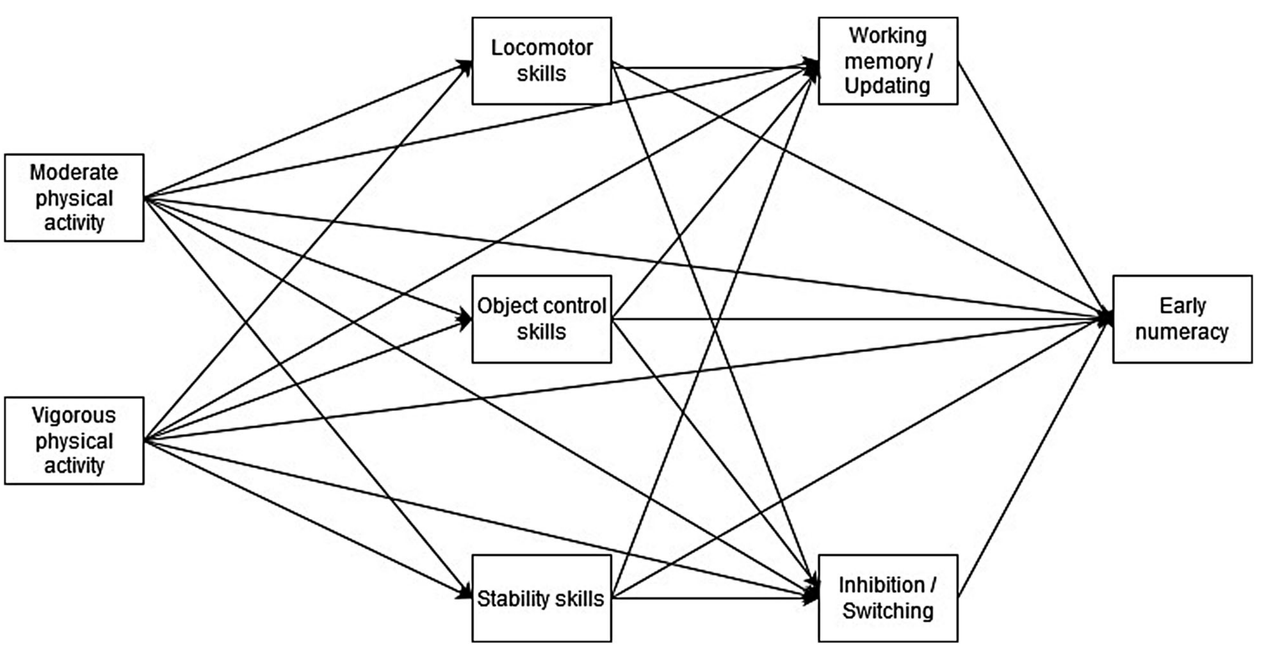

Figure 1. Hypothetical path model of the associations between moderate and vigorous physical activity, fundamental motor skills, executive functions and early numeracy.

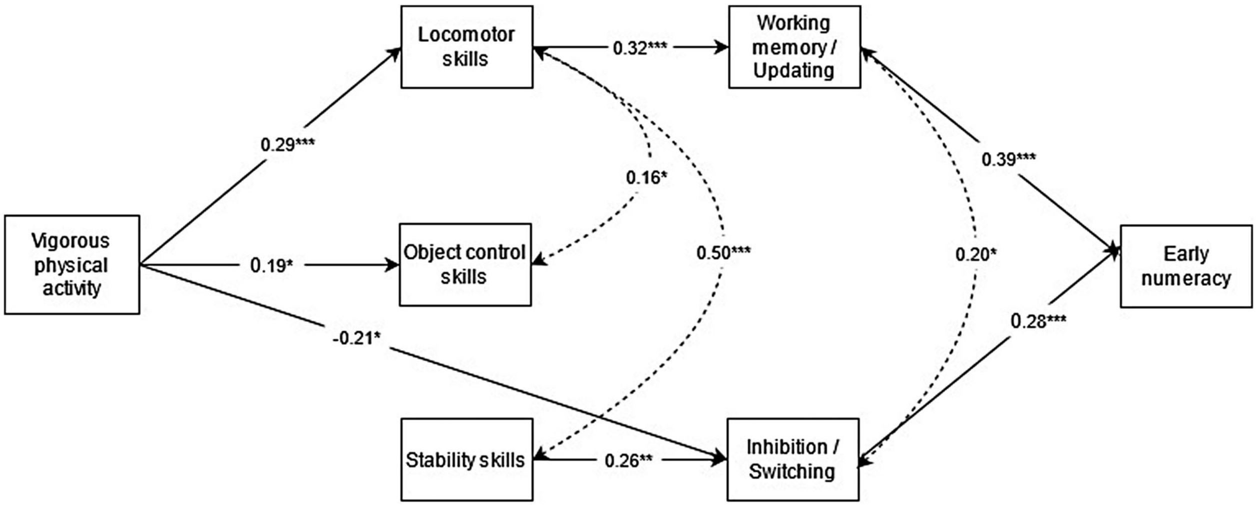

Figure 2. Statistically significant direct associations between vigorous physical activity, fundamental motor skills, executive functions and early numeracy (One-headed solid arrows). Double-headed dashed arrows represent residual covariance. ***$p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

model fit with the data: χ^2 (10) = 12.54, $p = 0.25$, CFI = .98, TLI = 0.96, RMSEA = 0.04, SRMR = 0.06 and explained 28% of the variance in the EN. The Wald test showed no gender differences in the significant path coefficients (χ^2 (10) = 2.147, $p = 0.9952$). VPA was positively associated with locomotor and object control skills, but not with stability skills. VPA was positively associated with working memory/updating and negatively associated with inhibition/switching. There was no direct statistically significant association of VPA with EN.

Locomotor skills were positively associated with working memory/updating, while stability skills were positively associated with inhibition/switching. There were no statistically significant associations of object control skills with EF or EN. Finally, both components of EF, working memory/updating and inhibition/switching, were positively associated with EN.

3.2. Indirect associations of motor skills and physical activity with early numeracy

First, indirect associations between FMS and EN through EF were examined. Second, indirect associations of VPA with EN through locomotor skills and EF were investigated. Two statistically significant indirect pathways were found between FMS and EN. Locomotor skills were positively associated with EN through working memory/updating ($\beta = 0.13$, $p = 0.001$, 95% CI [0.06, 0.20]). Stability skills were positively associated with EN through inhibition/switching ($\beta = 0.07$, $p < 0.05$, 95% CI [0.02, 0.14]). Two statistically significant indirect pathways were found between VPA and EN. VPA was positively associated with EN through locomotor skills and working memory/updating ($\beta = 0.04$, $p < 0.01$, 95% CI [0.02, 0.07]) and negatively associated with EN through inhibition/switching ($\beta = -0.06$, $p < 0.05$, 95% CI [−0.11, −0.02]). There was no total indirect association between VPA and EN ($\beta = -0.02$, $p = 0.445$, 95% CI [−0.08, 0.03]).

4. Discussion

The aim of this study was to investigate the direct and indirect cross-sectional associations of MPA and VPA, FMS, EF, and EN. We found that locomotor skills were positively indirectly associated with EN through working memory/updating and stability skills were positively indirectly associated with EN through inhibition/switching. There was also an indirect relation of VPA with EN through locomotor skills and working memory/updating. Interestingly, VPA was indirectly and negatively associated with EN through inhibition/switching.

Our first main finding indicated that children who accumulated more VPA also had better EN through locomotor skills and working memory/updating. The findings indicate that children spending more time in VPA also have better locomotor skills, which is linked to better working memory/updating and thus improved EN. Our findings are in line with the findings of a previous study (Nilsen et al., 2020) reporting that especially VPA is associated specifically with locomotor and object control skills in preschoolers. Physical activities offer children opportunities to develop their neuromotor abilities and are therefore vital for development of motor skills (Stodden et al., 2008). More studies are needed to better understand the associations between different intensity levels of PA and components of FMS. Most of the previous studies investigating the associations between PA, EF, and, EN in preschoolers have examined the amount of MVPA, but not MPA and VPA separately (Cook et al., 2019; Willoughby et al., 2018; Becker et al., 2014). Our findings together with those of McNeill and colleagues (McNeill et al., 2018; McNeill et al., 2020) implicate that MPA and VPA are differentially associated with EF and EN in preschoolers, emphasising the importance of studying causal relations more closely in future.

The relation between FMS and working memory has been found in previous studies which havereported associations of locomotor (TGMD-2) (Cook et al., 2019) and agility skills (obstacle course) (Niederer et al., 2011) with working memory in preschoolers. Locomotor tasks have high coordinative demands, which have been associated with improvements in parts of the brain important for EF, such as the cerebellum, the prefrontal cortex, and the basal ganglia, which leads to interrelated development of locomotor skills and working memory (Best, 2010). However, we did not find a significant association between preschoolers' locomotor skills and inhibition/switching. One explanation for the specific link between locomotor skills and working memory may be the working memory demand of locomotor activities in the TGMD test where children have to recall movement sequences, and the ability to avoid using irrelevant information (inhibition) is less needed. This is supported by the fact that all previous studies that have found links between motor skills and working memory in preschoolers have used tests requiring recall of specific sequences of activities (Cook et al., 2019; Niederer et al., 2011).

The second main finding in our study was that stability skills were positively and indirectly associated with EN through inhibition/switching, indicating that children with better whole-body coordination and balance skills most likely have better inhibition and switching ability, which can also be seen in better EN performance. Our finding that stability skills were associated with inhibition/switching is in line with previous observations by Oberer, Gashaj, and Roebers (2017) showing a strong positive association between stability skills and composite scores of EF in children aged six to seven years. Also, Niederer et al. (2011) reported a positive association between dynamic balance, one main component of stability, and working memory in preschoolers. Possible explanations for the link between stability skills and inhibition/switching are cognitive engagement required to execute complex motor movements, co-activation and the neural link between the cerebellum and the prefrontal cortex (Best, 2010), and common underlying cognitive processes involved in the motor and cognitive tasks as sequencing, monitoring, and planning (Roebers & Kauer, 2009). In addition, the association between children's stability skills and inhibition/switching has been explained by speed and accuracy demands inherent in stability and EF tasks (Roebers & Kauer, 2009). The relation between stability skills and mathematical performance through EF has been previously reported in school-aged children (Schmidt et al., 2017). Our study adds that this mediation effect of EF can be found already in preschoolers and it is particularly inhibition/switching component of EF mediating the relationship between stability skills and EN. Gashaj and colleagues (2019) found positive associations between preschoolers' stability skills and composite EF scores with EN: more precisely EF was positively related to the symbolic number line and magnitude comparison tasks, and stability skills with nonsymbolic magnitude comparison skills. We found that stability skills and EF are positively associated with a holistic measure of EN (incl. numerical relational and counting skills). These diverse findings highlights that more research is needed to understand how various components of EF, EN and motor skills are developmentally related.

Our third main finding was that a child who had higher amounts of VPA also had weaker EN, possibly due to weaker inhibition/switching skills. Previous studies have reported negative association of MVPA with composite scores of EF (Willoughby et al., 2018) and with working memory in preschoolers (Cook et al., 2019). It has been suggested that children with more hyperactive impulses might engage in MVPA in types of activities that do not facilitate cognitive development (Willoughby et al., 2018). Furthermore, this relationship has been explained through hyperactive-impulsive behaviours as children with hyperactive-impulsive behaviours may also have executive dysfunction (Cook et al., 2019). Our findings suggest that it is particularly VPA and inhibition/switching that are negatively associated, although there was a positive relation between VPA and working memory/updating. Clearly, we need more longitudinal studies using different PA intensity levels, various EF and academic skills components to understand the effects of PA to learning in early childhood.

Important strengths of our study were device-based measurement of PA and valid and comprehensive assessment of FMS and EF. Furthermore, this was the first study in preschoolers where all components of FMS were investigated together with EF and EN. However, accelerometers, a method used to investigate PA in our study, measures amount and intensity of PA. There can be other aspects in physical activities which explain the relation between PA and EF, such as cognitive engagement inherent in PA (e.g. in team sport)

(Best, 2010). Furthermore, children participating in this study had very high levels of MPA and VPA, which might affect the results. It might be that there is a certain level of PA beyond which increasing the amount or intensity of PA no longer has beneficial effects on EF. Because 97% of the children met the PA recommendations (at least 3 h PA per day of which one hour is MVPA) (The Ministry of Education and Culture, Finland, 2016) we were unable to investigate whether accumulating MPA to VPA below the recommended levels is linked with weaker EF and EN. Therefore, generalising our results to other populations with low levels of PA should be made with caution. These high amounts of PA found in our study might be explained through cultural aspects, as Finnish children have shown to be highly physically active during pre-school days. The amount of moderate and vigorous physical activity was analyzed based on age-appropriate cut-points reported by Pate et al. (2006). The use of cut-points has its limitations as the amount of time spent in different intensity levels might change depending on the selected cut-points. Thus, using other cut-points might have changed the results. However, similar cut-points for MPA and VPA have been used in previous studies investigating associations between MPA and VPA and EF (Cook et al., 2019; McNeill et al., 2018; McNeill et al., 2020) making our findings comparable with previous studies in this age group. We only used one task to measure each component of EF and only accuracy scores were used in the analysis. More tasks to measure one component would give a more holistic of children's abilities in each component of EF. Because of cross-sectional study design, causal relationships could not be examined.

5. Conclusions

Our findings indicate that by providing opportunities for VPA and supporting motor skills learning, it may be possible to promote EF and EN in preschoolers. Longitudinal and intervention studies are needed to more closely investigate causal relationships and developmental dynamics between various components of PA, FMS, EF and EN.

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