THE BRAIN IN MOTION

EFFECTS OF DIFFERENT TYPES OF PHYSICAL ACTIVITY ON PRIMARY SCHOOL CHILDREN'S ACADEMIC ACHIEVEMENT AND BRAIN ACTIVATION

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1

GENERAL INTRODUCTION

1.1. BACKGROUND

These days, children spend an increasing amount of time in sedentary activities, with many children not meeting the recommended daily amount of physical activity (Verloigne et al., 2012). Relatedly, children's physical fitness (World Health Organization, 2017) and levels of motor skills (Inspectorate of Education, 2018) are decreasing. These numbers are worrisome, as physical fitness and motor skills are important aspects of children's health (Ortega, Ruiz, Castillo, & Sjöström, 2008; Robinson et al., 2015). Furthermore, physical activity during childhood is important for physical health and functioning across the lifespan (Telama et al., 2005), for children's emotional development, social skills and relations (Eime, Young, Harvey, Charity, & Payne, 2013), and for remaining physically active throughout life (Janz, Dawson, & Mahoney, 2000).

Many studies in recent years have shown that both physical fitness and motor skills are also positively linked to children's academic performance. Although the exact relations are poorly understood, studies have shown that fitter children in general perform better at school (see Santana et al., 2016), and that better developed motor skills are related to higher academic achievement (see Macdonald, Milne, Orr, & Pope, 2018). In line with these results, there is more and more evidence for the positive effects of physical activity interventions on children's academic performance in primary school (see de Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018a). The effectiveness of this type of interventions seems to differ depending on characteristics of the child, and the intervention (Vazou, Pesce, Lakes, & Smiley-Oyen, 2016), underlining the importance of identifying what works for whom.

As children spent a large part of their active day at school (Pate et al., 2006), it is unfortunate that typical Dutch school curricula have children spend around 66% of their time at school in sedentary behavior (van Stralen et al., 2014). Schools are under great pressure to improve children's academic achievement and many educators therefore believe that formal academic topics (i.e. reading, spelling and mathematics) should be preferred over physical education (Chaddock, Pontifex, Hillman, & Kramer, 2011). Following the results on relations between the physical and cognitive domain, it can be questioned whether these beliefs are true. Lower levels of physical activity and relatedly physical fitness and motor skills may not only result in poorer physical health outcomes, but also in poorer academic performance. It therefore seems vital to identify the relations between the physical and the academic domain, and to consequently develop interventions that simultaneously target children's physical development, as well as their academic achievement.

1.2 THEORETICAL FRAMEWORK

Academic achievement in language and mathematics is considered extremely important for children in primary school, because these academic skills provide a foundation for children's development. Children need an adequate level of these skills in order to perform well in other subjects such as geography and history, and to be successful in their future career (Onderwijsraad, 2011). Consequently, children with low academic achievement are likely to suffer from their academic difficulties, being at risk for being referred to special education, repeating class, and school drop-out in secondary education (Rumberger & Lim, 2008; van der Veen, Smeets, & Derriks, 2010).

There is extensive evidence on the association between children's academic achievement and their levels of physical fitness and motor skills (see Santana et al., 2016 and Macdonald et al., 2018). Physical fitness refers to a set of health and skill-related capacities needed to perform various physical activities (Keeley & Fox, 2009). The link between the physical and academic domain seems to be the most valid for the cardiovascular aspects of physical fitness (called 'aerobic fitness'; Santana et al., 2016), referring to the capacity to be physically active for a prolonged period of time (Caspersen, Powell, & Christenson, 1985). Motor skills are learned sequences of movements that are combined to executive smooth, efficient actions needed to fulfill particular tasks (Gallahue, Ozmun, & Goodway, 2012). Motor skills can be divided into fine and gross motor skills, of which gross motor skills in particular are important building blocks for adopting a physically active lifestyle (e.g. Stodden et al., 2008).

Physical fitness and motor skills are related aspects of children's physical development, with fitter children in general also having better developed motor skills (e.g. Lubans, Morgan, Cliff, Barnett, & Okely, 2010). Unfortunately, not much research has taken this interrelation into account when examining relations between physical and academic skills. It is therefore poorly understood how physical fitness and motor skills are related to academic achievement. To increase this understanding, the first part of this dissertation will focus on deepening our knowledge on the relations between physical fitness and motor skills on the one hand, and academic achievement in reading, mathematics, and spelling on the other hand.

1.2.1 EXECUTIVE FUNCTIONS AND ACADEMIC ACHIEVEMENT

The strongest relations with physical fitness and motor skills have been found for a specific subset of cognitive skills, namely executive functions (Tomporowski, Lambourne, & Okumura, 2011), the cognitive functions that guide and control goal-directed behavior (Diamond, 2013). Executive functions are generally subdivided into three categories: inhibition, working memory (verbal and visuospatial) and shifting (Miyake et al., 2000). They are critical skills for a successful academic career, and for success throughout life in general (Diamond, 2013). Accordingly, academic achievement strongly relies on skills as inhibiting impulsive behavior, planning, updating of working memory, and flexible shifting of attention. It is therefore not surprising that low academic achievement often goes hand-in-hand with lower levels of executive functioning (van der Sluis, de Jong, & van der Leij, 2004; van der Sluis, van der Leij, & de Jong, 2005). Executive functions could consequently provide an explanation for the relations between physical and academic skills, making well-developed executive functions imperative for improving academic achievement. There is some first evidence showing that executive functions act as a mediator in the relation between physical fitness and academic achievement (van der Niet, Hartman, Smith, & Visscher, 2015), and between motor skills and academic achievement (Rigoli, Piek, Kane, & Oosterlaan, 2012a; Schmidt et al., 2017), supporting the idea that the positive effects of physical activity on academic achievement are brought about via improved executive functioning.

Interestingly, the executive functions needed for good academic performance are found to differ per academic domain (Lubin, Regrin, Boulc'h, Pacton, & Lanoë, 2016). Likewise, from research in children with academic difficulties it is known that the pattern of executive function deficit differs depending on the domain of low performance, with low achievers in reading having problems with different executive functions than low performers in mathematics (e.g. Tang, 2007; van der Sluis et al., 2004; 2005). This suggests that the relations between physical, cognitive, and academic skills are domain-specific as well. Until now, not much research has focused on the mediating relations of executive functioning however, leaving the exact ways in which physical, cognitive, and academic skills are linked unknown. To get a better understanding of the domain-specificity of these mediating relations, it will be examined in this dissertation how executive functions mediate the relation between physical fitness and achievement in the different domains of mathematics and spelling, with a special focus on low academic achievement.

1.2.2 DIFFERENCES IN BRAIN STRUCTURE AND FUNCTIONING

In order to explain the relations between children's physical abilities on the one hand, and their cognitive and academic skills on the other hand, several studies have started to explore the brain structures and functions that might be underlying these relations, by being involved in physical as well as cognitive performance. Fitter children are found to have greater volumes of (sub)cortical structures that are critical for learning and memory, including the hippocampus and basal ganglia (see Donnelly et al., 2016). Although literature on the relation between physical fitness and brain activation is scarce, fitter children seem to show larger activation in frontal and parietal regions during executive functioning tasks, mainly in brain areas important for, amongst others, monitoring of behavior (anterior cingulate cortex), and attentional control (middle and inferior frontal gyrus and precentral gyrus; see Donnelly et al., 2016). Few studies have focused on the relations of motor skills with brain structure and functioning. There are some indications of co-activations between the prefrontal cortex, cerebellum and basal ganglia during several motor and cognitive tasks, especially when a task is difficult or new, conditions of a task change, a quick response is required, and concentration is needed to perform a task (Budde, Koutsandréou, & Wegner, 2017; Diamond, 2000). To further our understanding of how children's physical fitness and motor skills are related to their brain activation, this dissertation will examine the relations between physical fitness, motor skills, and brain activation during a cognitive task.

1.2.3 EFFECTS OF PHYSICAL ACTIVITY ON ACADEMIC ACHIEVEMENT

The interrelations between the physical and cognitive domain suggest that improvements in physical fitness and motor skills could also have positive effects on cognitive and academic performance. Physical activity interventions could be helpful in this sense, as there is evidence that this type of intervention can have positive effects on children's physical fitness (Sun et al., 2013) and motor skills (Morgan et al., 2013). Physical activity can be defined as all bodily movements produced by muscle activity that increase energy expenditure above normal physiological demands (Ortega et al., 2008). Following this hypothesis, physical activity indeed has been shown to have positive effects on children's cognition and academic performance (see de Greeff et al., 2018a). The effects of physical activity on executive functioning are generally found to be stronger than the effects on academic achievement, because academic achievement is a more global aspect of cognition (see Aadland et al., 2017). Still, as executive functioning is an important predictor of academic achievement (Diamond, 2013), it is not surprising that physical activity interventions not only have positive effects on executive functioning, but also on academic achievement. A recent meta-analysis by de Greeff and colleagues (2018a) concluded that there was a small to moderate positive effect (effect size (ES) = 0.26) of longitudinal physical activity interventions on academic performance. This result is in line with the small to moderate effect (ES = 0.27) that was found in a previous meta-analysis by Fedewa and Ahn (2011), supporting the idea that physical activity can have beneficial effects on academic performance of children in primary school.

There are indications that the effectiveness of physical activity programs differs depending on the academic domain involved. Singh and colleagues (2019) reported the strongest effects of physical activity on children's mathematics achievement. A meta-analysis by de Greeff and colleagues (2018a) on the other hand only found effects on overall academic achievement, not on performance in any of the subdomains, although it should be noted that the number of included studies per subdomain was low. To deepen our knowledge on the differential effects of physical activity on performance in the subdomains of academic achievement, the effects on the subdomains of reading, mathematics, and spelling will be studied separately in this dissertation.

Also, the effectiveness of this type of physical activity interventions is thought to depend on children's initial performance level, as several studies suggest that physical activity is the most effective for children who have the lowest cognitive and academic performance at the start, possibly because they have most room for improvement (Diamond, 2012; Diamond & Lee, 2011; Drollette et al., 2014; Sibley & Beilock, 2007). Therefore, children's initial achievement level will be taken into account in this dissertation as well.

1.2.4 MECHANISMS UNDERLYING EFFECTS OF PHYSICAL ACTIVITY

Several mechanisms have been brought forth to explain effects of physical activity on cognition and academic achievement. As most research on the effects of physical activity has sought the explanation for these effects in the neurobiological domain, referring to changes in the brain, it was decided to follow this framework in the current dissertation as well. According to physiological mechanisms, one bout of physical activity at a moderate-to-vigorous intensity level (MVPA; also termed aerobic physical activity) results in an increased release of neurotransmitters (e.g. brain-derived neurotrophic factor) and monoamines (e.g. dopamine, epinephrine). After continuous aerobic physical activity of several weeks, these increases will result in the development of new neurons (neurogenesis) and blood vessels (angiogenesis) in brain areas that support learning and memory (Best, 2010). Also, continuous aerobic physical activity is thought to result in the development of new connections, and strengthening of existing connections between brain areas (neuroplasticity).

These long-term changes in brain structure and functioning are consequently expected to support cognitive and academic performance (Alvarez-Bueno et al., 2017; Best, 2010; Donnelly et al., 2016). Evidence for this hypothesized mechanism has been provided by animal studies. Also, some first studies in adults and children have provided support for these mechanisms (see Best, 2010; Donnelly et al., 2016).

A more recently provided mechanism is the cognitive stimulation hypothesis, in which it is emphasized that physical activity that is cognitively-engaging is even more beneficial for cognition and academic achievement than 'simple' aerobic physical activities (Crova et al., 2014; Pesce, 2012). Cognitive engagement refers to the requirement of cognitive effort, the allocation of attention, and the use and coordination of complex motor skills (Tomporowski, McCullick, Pendleton, & Pesce, 2015). This type of physical activity is for example often seen in team sports, where participants have to focus their attention, plan a strategy, collaborate with team mates, coordinate movements, and so on. According to the cognitive stimulation mechanism, the same brain areas are recruited during this type of physical activity as those that are needed for cognitive task performance (Diamond & Lee, 2011; Pesce, 2012). Particularly a co-activation of the prefrontal cortex and cerebellum is often mentioned (see Budde et al., 2017). Because these brain areas are already co-activated during physical activity, they can be used more efficiently during cognitive and academic task performance as well.

Following the mechanisms described above it can be expected that effects of physical activity on cognition and academic achievement depend on the type of physical activity involved. The most-consistent evidence has been provided for aerobic physical activity (Best, 2010, also see Donnelly et al., 2016). Interestingly, a recent meta-analysis found that cognitively-engaging physical activity programs had the strongest effects on executive functioning, reporting a moderate to large positive effect, compared to a small to moderate effect for aerobic physical activity (de Greeff et al., 2018a). At the moment, too few studies have examined effects of different types of physical activity on academic achievement, leaving it unknown whether cognitively-engaging physical activity is also more effective in improving academic achievement than aerobic physical activity. Yet, regarding the close link between executive functioning and academic achievement (Diamond, 2013), this result can be expected, making cognitively-engaging physical activity an interesting topic for further research. To increase our knowledge on the type of physical activity that is most beneficial for improving academic achievement, the aim of this dissertation is to examine the effects of two types of physical activity, cognitively-engaging physical activity and aerobic physical activity, on academic achievement.

The distinct effects of different types of physical activity on cognitive and academic performance are argued to be brought about via structural and functional changes in brain areas that support learning and cognition. Aerobic physical activity is thought to have different effects on brain structure and functioning compared to cognitively-engaging physical activity that more strongly relies on motor skills (Voelcker-Rehage & Niemann, 2013). Animal studies have already provided evidence for the difference in underlying brain changes as a result of aerobic compared to complex, coordinative physical activity (see Voelcker-Rehage & Niemann, 2013). At the moment, evidence on effects of physical activity on the human brain is still scarce however. Overall the results suggest that physical activity results in activity changes in the prefrontal and parietal cortex (see Donnelly et al., 2016). Whether these changes are also related to improvements in cognition and academic achievement has not yet been studied, and the exact type of physical activity that is needed to trigger brain changes that are related to cognition and academic performance remains unknown. To answer these questions, the last part of this dissertation will focus on the effects of different types of physical activity (aerobic vs. cognitively-engaging) on children's brain activation. This will increase our understanding of the mechanisms by which physical activity affects academic achievement.

1.3 AIMS AND OUTLINE OF THIS DISSERTATION

The main aim of this dissertation is to examine the effects of different types of physical activity (aerobic and cognitively-engaging) on primary school children's academic achievement and underlying brain activation. First, relations between physical fitness, motor skills, executive functions, brain activation and academic achievement are explored. Following, the effects of two types of physical activity interventions on academic achievement and brain activation are examined. This dissertation is part of a larger project, in which also the effects on physical fitness, motor skills, and executive functioning are studied (see de Greeff et al., 2018b).

Chapter 2 gives an overview of the direct and indirect relations between physical fitness, executive functioning, and low academic achievement. In this chapter, it is examined whether physical fitness is directly related to low academic achievement in mathematics and spelling, or whether physical fitness is predictive of low academic achievement via executive functioning. Four main categories of executive functioning (inhibition, verbal working memory, visuospatial working memory, and shifting) are examined as mediators, to examine whether the relations between physical fitness, executive functioning, and low academic achievement are specific depending on the academic domain (mathematics or spelling) involved.

In **Chapter 3**, the differential relations between aerobic fitness and academic achievement, and between motor skills and academic achievement are examined. It is hypothesized that the relation between motor skills and academic achievement will be stronger than the relation between physical fitness and academic achievement. Further, different relations between physical fitness and motor skills on the one hand, and academic achievement on the other hand are expected, depending on the academic domain involved.

These relations are examined in the domains of reading comprehension, mathematics and spelling.

Chapter 4* presents children's brain activation pattern during a visuospatial working memory task (measured with functional MRI), and its relations with physical fitness and motor skills. A subsample of 90 children of the intervention study (Chapter 5) took part in a MRI protocol, in which their brain activation during a visuospatial working memory task was measured. It is hypothesized that fitter children, and children with better developed motor skills, will show different brain activation patterns compared to their less fit peers, and peers with less well-developed motor skills. As literature on these relations is still scarce, there are no hypotheses regarding the specific brain areas that will show differences in activation.

In **Chapter 5** the effects of two physical activity interventions on academic achievement are described. Children from 22 primary schools in the Netherlands participated in a cluster randomized controlled trial (RCT) in which the intervention groups followed a 14-week physical activity intervention program, either focused on aerobic physical activity, or on cognitively-engaging physical activity. The intervention programs were implemented four times a week by specialist teachers, during regular and extra physical education lessons. The aerobic intervention program focused on physical activity at a moderate-to-vigorous intensity level, the cognitively-engaging physical activity intervention program involved complex exercises and movements. The control group followed their regular physical education lessons, two times a week. Academic achievement in reading comprehension, mathematics, and spelling at posttest is compared for the three groups. It is expected that children in the intervention groups will perform better at posttest than children in the control group, with the largest differences for children who followed the cognitively-engaging intervention program.

In **Chapter 6**[*], the effects of the two physical activity interventions on brain activation during a visuospatial working memory task are examined. The same sample of children as in Chapter 4 participated. Brain activation during the visuospatial working memory task was measured before and after the 14-week intervention programs. The changes in brain activation patterns between pretest and posttest are compared for the three groups (control group, aerobic intervention group, and cognitively-engaging intervention group). It is expected that children in the intervention groups will show larger changes in brain activation than children in the control group. No specific hypotheses regarding the brain areas that will show changes in activation or the specific effects for the two interventions are formulated, because of a lack of research on this topic in children.

Finally, **Chapter 7** presents an overview of the most important results of this dissertation, and discusses these in light of the existing knowledge. In addition, limitations are discussed, and practical implications and suggestions for future research are given.

[*] These two chapters have shared first authorship with I. M. J. van der Fels. Both authors have equally contributed to these articles, order of authors is alphabetically

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2

EXPLORING THE RELATIONS AMONG PHYSICAL FITNESS, EXECUTIVE FUNCTIONING AND LOW ACADEMIC ACHIEVEMENT

This chapter is based on:
de Bruijn, A. G. M.
Hartman, E.
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Visscher, C.,
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Exploring the relations among physical fitness, executive functioning and low academic achievement. *Journal of Experimental Child Psychology*, *167*, 204-221. doi: 10.1016/j.jecp.2017.10.010

ABSTRACT

Physical fitness seems to be related to academic performance, at least when taking the role of executive functioning into account. This assumption is highly relevant for the vulnerable population of low academic achievers because their academic performance might benefit from enhanced physical fitness. The current study examined whether physical fitness and executive functioning are independent predictors of low mathematics and spelling achievement or whether the relation between physical fitness and low achievement is mediated by specific executive functions. In total, 477 students from second- and third-grade classes of 12 primary schools were classified as either low or average-to-high achievers in mathematics and spelling based on their scores on standardized achievement tests. Multilevel structural equation models were built with direct paths between physical fitness and academic achievement and added indirect paths via components of executive functioning: inhibition, verbal working memory, visuospatial working memory, and shifting. Physical fitness was only indirectly related to low achievement via specific executive functions, depending on the academic domain involved. Verbal working memory was a mediator between physical fitness and low achievement in both domains, whereas visuospatial working memory had a mediating role only in mathematics. Physical fitness interventions aiming to improve low academic achievement, thus, could potentially be successful. The mediating effect of executive functioning suggests that these improvements in academic achievement will be preceded by enhanced executive functions, either verbal working memory (in spelling) or both verbal and visuospatial working memory (in mathematics).

2.1 INTRODUCTION

There is accumulating evidence for relations between the physical and the cognitive domain. Children with higher levels of physical fitness perform better cognitively, as shown by their academic abilities in mathematics, reading, and language (Fedewa & Ahn, 2011; Santana et al., 2016). Physical fitness can be defined as a set of characteristics used to perform physical activities (Ortega, Ruiz, Castillo, & Sjöström, 2008). It entails the full range of physical capacities and can be subdivided into various components, for instance aerobic fitness, muscular strength, and skill-related fitness. The relation between physical fitness and academic achievement seems to be especially strong in the domain of mathematics (Chaddock-Heyman et al., 2015; Chomitz et al., 2008; Lambourne et al., 2013), although relations have also been found for reading (e.g. Chomitz et al., 2008) and spelling (Pindus et al., 2016).

Interestingly, physical fitness has not only been related to academic achievement, but also to other cognitive functions, such as executive functioning (see Chaddock, Pontifex, Hillman, & Kramer, 2011). Executive functions are a subset of higher-order cognitive functions that are involved in organizing and controlling goal-directed behavior (Diamond, 2013). Three core executive functions are generally distinguished: inhibition, shifting, and working memory (Miyake et al., 2000). Inhibition is defined as the ability to withhold dominant, automatic behaviors that are irrelevant for the task at hand. Shifting, or task switching, refers to the ability to shift attention forwards and backwards between multiple tasks in order to easily adapt to changing situations. Verbal and visuospatial working memory are required for the monitoring and coding of incoming information in order to revise and replace information that is no longer relevant by new, more useful information. Well-developed executive functions are a prerequisite for good academic performance. Reading, spelling, and mathematics are complex skills that rely heavily on the ability to inhibit automatic behavior, to shift between strategies, and to update working memory (Best, Miller, & Naglieri, 2011).

2.1.1 EXPLANATORY MECHANISMS

Several explanations have been proposed to account for the relationship between physical activity and executive functioning. Generally, these mechanisms can be categorized into two broad categories: physiological mechanisms and learning/developmental mechanisms. According to physiological mechanisms, aerobic activity at a moderate-to-vigorous intensity level leads to an upregulation of several growth factors (e.g. brain-derived neurotrophic factor) and monoamines (dopamine, epinephrine and norepinephrine), resulting in short- and long-term changes in the structure and functioning of brain regions that are responsible for learning (Best, 2010). Learning/developmental mechanisms explain the relation between physical activity and cognition by referring to the learning experiences that take place while being physically active, which have beneficial effects on cognitive development as well. In this sense, it is not the physical exertion per se that is important, but rather the cognitive engagement during physical activity and the cognitive demands inherent in motor skill learning and coordination of complex movements (Sibley & Etnier, 2003). It has been suggested that both mechanisms are complementary, meaning that a combination of moderate-to-vigorous physical activity and cognitive-demanding activities will have the strongest effects on executive functioning (Kempermann et al., 2010).

As executive functions are essential cognitive skills for good academic performance and because physical fitness seems to be related to both executive functioning and academic achievement, it can be hypothesized that the relation between physical fitness and academic achievement goes via executive functioning (Howie & Pate, 2012). A study by van der Niet, Hartman, Smith and Visscher (2014) provided the first support for the mediating effect of executive functioning by reporting that the direct relation between physical fitness and academic achievement disappeared once executive functioning was taken into account. It thus seems that beneficial effects of physical fitness on academic achievement are brought about via improved executive functions.

2.1.2 LOW ACADEMIC ACHIEVEMENT

This assumption is highly relevant when considering the population of low academic achievers, which we define as the lowest 25% performing students in one or more academic domains (Siegel, 1999). This < 25% criterion is widely used as criterion for having low achievement and/or learning difficulties (e.g. Geary, 2013; Geary & Hoard, 2005; Swanson & Jerman, 2006; see also Murphy, Mazzocco, Hanich, & Early, 2007 for a review on cutoff criteria for mathematical difficulties). There is evidence for the validity of this cutoff score for example from studies showing that students with learning difficulties can be separated from their normally achieving peers on different types of tasks based on this cutoff (see Siegel 1999). Only a few studies have focused on this specific population, however, which is unfortunate, as low achievement in school can have devastating consequences for a child's development. Poor academic performance greatly increases the likelihood of being referred to special education (van der Veen, Smeets & Derriks, 2010). This referral can hamper cognitive development of low achieving students even more, as they seem to make more progress in regular than in special education (Baker, Wang, & Walberg, 1994; Lipsky & Gartner, 1996; Peetsma, Vergeer, Roeleveld, & Karsten, 2001). In addition, low academic achievement in primary school is a strong predictor of dropping out of school altogether (Rumberger & Lim, 2008).

In line with the hypothesis that executive functioning mediates the relation between physical fitness and academic achievement, results indicate that lower academic performance is related to lower levels of executive functioning (van der Sluis, de Jong, & van der Leij, 2004; van der Sluis, van der Leij, & de Jong, 2005). The pattern of cognitive deficit seems to depend on the domain of low performance, with learning-lagged students in the domain of language showing different deficits than those in the domain of mathematics (Tang, 2007). The relation between executive functioning and academic performance seems to be especially strong in the domain of mathematics (Bull & Lee, 2014; Cragg & Gilmore, 2014), where the most pronounced relations have been found with working memory (de Smedt et al., 2009; Passolunghi, Mammarella, & Altoè, 2008). The few studies that specifically examined children with spelling disorders only focused on working memory and found that spelling problems were related to worse performance on verbal working memory, but not on visuospatial working memory (Brandenburg et al., 2014; Wimmer & Mayringer, 2002; Wimmer & Schurz, 2010).

The problems associated with low academic achievement underline the need for early intervention. As the poorer academic performance of low achievers seems to be related to less well-developed executive functions and lower levels of physical fitness, improvements in physical fitness, by being related to executive functioning, could be beneficial for academic performance. There are indeed indications that physical activity interventions are particularly successful for students with cognitive and/or physical problems, probably because they have the most room for improvement (Diamond, 2012; Diamond & Lee, 2011; Drollette et al., 2014; Sibley & Beilock, 2007). Empirical evidence for the mediating effect of executive functioning is still scarce, however, and it remains unknown whether there are specific direct and indirect relations between physical fitness, executive functioning, and academic achievement. Considering the need for interventions, particularly for students with low academic achievement, research is necessary to determine whether executive functions mostly fulfil a mediating role between physical fitness and academic achievement, or that executive functions and physical fitness each have strong direct relations with academic achievement.

2.1.3 THE PRESENT STUDY

Therefore, the present study aims to examine the relation between physical fitness and low academic achievement in mathematics and spelling. As there are strong relations between physical fitness and executive functioning, and between executive functioning and academic achievement, it will be examined whether physical fitness and executive functioning are independently related to academic achievement in mathematics and spelling or whether executive functioning is a mediator in the relation between physical fitness and low academic achievement in these domains. Following Miyake and Friedman's theory of executive functioning (2000) which states that there are three core executive functions, the following executive functions will be taken into account: inhibition (Stroop test), working memory (verbal- Digit span task, visuospatial- Visual span task) and shifting (Modified Wisconsin Task Sorting Test). Previous studies have shown that there are specific relations between physical fitness and academic achievement (e.g. Chaddock-Heyman et al., 2015), and executive functioning and academic achievement (e.g. Tang, 2007). It is therefore expected that there are specific mediating relations between physical fitness and components of executive functioning, depending on the academic domain involved. In order to examine these specific relations, the four executive functions mentioned above will be taken into account as separate variables.

2.2 METHODS

2.2.1 PARTICIPANTS

A total of 510 children of twelve primary schools in the Northern part of the Netherlands took part in this study. Children were in second or third grade (Mean age = 8.05, *SD* = .72). Not all participants were included for analyses due to missing data (*N* = 33), resulting in a total sample of 477 children. Five participants had missing values on mathematics achievement and four other participants on spelling achievement. These participants were left out of analysis in that specific domain, leaving 472 participants for mathematics and 473 participants for spelling. The study was approved by the Ethics Committee of the Center for Human Movement Sciences of the University Medical Center

Groningen, University of Groningen. Informed consent was provided for all children by their legal guardian.

Children were classified into five achievement levels (A-scores, B-scores, C-scores, D-scores or E-scores) for the domain of mathematics and the domain of spelling based on their norm-referenced scores on a standardized national achievement test. Children with A-scores represent the 25% highest performing children on the standardized achievement test. B-scores represent the 25% of students who perform far to just above the national average. Students with C-scores are the 25% of students who score just- below to far below the average national score. D-scores represent the 15% of students who perform far-below the national average. Students with E-scores are the 10% lowest performing children. We grouped students with D-scores and E-scores together into one group making up the lowest 25% performing students and classified them as low academic achievers. The other three groups (75%) were grouped together as well and were classified as average-to-high achieving students. Children of the lowest achievement level (< 25%) were consequently compared to children of the other three achievement levels by creating a dichotomous variable (low achievers vs. average-to-high achievers). Descriptive statistics of the low achieving and higher achieving groups are shown in Table 2.1.

TABLE 2.1. Descriptive statistics of low- achieving and average-to-high achieving children in mathematics and spelling.

	Mathematics		Spelling	
	Low (*n* = 73)	Average-to-high (*n* = 399)	Low (*n* = 52)	Average-to-high (*n* = 421)
Age (yr.)	8.1 (.7)	8.0 (.7)	8.3 (.8)	8.0 (.7)
Grade				
Second	41 (56%)	200 (50%)	18 (35%)	221 (52%)
Third	32 (44%)	199 (50%)	34 (65%)	200 (48%)
Gender				
Boys	26 (36%)	182 (46%)	32 (61%)	178 (42%)
Girls	47 (64%)	217 (54%)	20 (39%)	243 (58%)

Note. Values are mean ± standard deviation for age only, and n (%) for grade and gender.

2.2.2 MATERIALS

PHYSICAL FITNESS TESTS

Four subtests of the standardized Eurofit test battery (van Mechelen, van Lier, Hlobil, Crolla, & Kemper, 1991) were used to measure four aspects of physical fitness: aerobic fitness (20m shuttle run, in number of completed tracks), muscular strength (standing broad jump, in centimeters), running speed and agility (10x5m shuttle run, in seconds) and upper-limb agility (plate-tapping, in seconds). The Eurofit is a reliable (r = .62 to .97) and valid measure of children's fitness (Adam, Klissouras, Ravazzolo, Renson, & Tuxworth, 1988), and has been well established in previous studies (Fransen et al., 2014).

The 20m endurance shuttle run test was used as a measure of aerobic fitness. In this test, children ran back and forth between two lines that are 20m apart within a specific time interval that was indicated by audio signals. The interval between each successive signal became smaller as the test proceeded. The test ended when a child failed to reach a line prior to the signal on two successive trials. The number of completed tracks was recorded as final score.

Muscular strength was measured with the standing broad jump test (SBJ). In this test, children stood behind a line with their feet slightly apart. They used a two-foot take-off to jump as far as possible, swinging the arms to create forward drive and landing on both feet again without falling backwards. Children got two attempts of which the longest distance jumped (in cm) was recorded as a test result.

As a measure of skill-related physical fitness, measures of both upper-limb and lower-limb were recorded. The 10x5m shuttle run test was administered to measure speed and agility of lower limb movement. In this test, children ran back and forth between two lines that were 5m apart. The time needed to run this distance ten times (50m in total) was recorded.

The plate-tapping test measures speed of upper-limb movement. In this test, children had to alternately touch two discs that were 80cm apart as fast as possible. The time needed to complete 25 full cycles was recorded. The best of two attempts was used as a test result.

EXECUTIVE FUNCTIONING

Inhibition. The Stroop task was used as a measure of inhibition (Golden, 1978). Children were presented with three cards resembling three conditions. In the first condition, children were asked to read aloud a series of color words printed in black ink (Word task). In the second condition children had to name the color of rectangles (printed in red, yellow, green or blue ink: Color task). The last condition presented children with the names of colors printed in conflicting colors (in red, yellow, green or blue) of which children had to name the color of the ink (Color-word task). In each condition, children had 45 seconds to name as many words or colors as possible. The number of correctly named words or colors was used as a score for the respective condition, with a maximum score of 100 for each condition. A Stroop inference score was calculated by subtracting the score of the Color task from the score of the Color-Word task. The Stroop inference score has proven to be a reliable measure for measuring inhibition in children (test-retest reliability is .81; Neyens & Aldenkamp, 1997).

Verbal working memory. The Digit span backward task was used to measure verbal working memory (Wechsler, 1987). In the Digit span backward the instructor read aloud a sequence of digits and asked the child to recall this sequence in a reverse order. Spans increased from two to eight digits, with three sequences in a span, making up a maximum score of 21. The test was stopped when a child failed to correctly recall at least two of the three sequences within one span. The digit span backward is a reliable (test re-test reliability is .82) and valid measure of children's verbal working memory (Wechsler, 1987).

Visuospatial working memory. The Visual span backward task was used as a measure of visuospatial working memory (Wechsler, 1987). In this task, children had to repeat a sequence of squares tapped on a card containing eight printed squares in reverse order. The number of tapped sequences increased from two to seven. The child had to repeat two different sequences within each span, resulting in a maximum score of twelve. The test ended when a child failed to recall two sequences of the same length. The Visual span backward is a reliable (test re-test reliability is .75) and valid measure of visuospatial working memory in children (Wechsler, 1987).

Shifting. A modified version of the Wisconsin Card Sorting test (MWCST) was used to measure shifting. The MWCST is an adapted version of the regular Wisconsin Card Sorting test and is considered more appropriate for children (Cianchetti, Corona, Foscoliano, Contu, & Sannio-Fancello, 2007). In this test, the child received 48 cards, each of which has a unique color (red, yellow, blue or green), unique shape (circle, cross, triangle or star) and unique number of shapes (one, two, three or four). The child had to sort these cards according to one of the characteristics by using feedback on whether a card was sorted correctly or incorrectly. The sorting rule changed after six consecutive correct responses. The task ended when all 48 cards were sorted or when six different sorting rules were used within six consecutive trials. Two scores were used to measure categorizing ability: number of perseverative errors (i.e. a failure to change the sorting rule after negative feedback) and categorizing efficiency, which was calculated by granting six points to every correctly applied sorting rule and one point to each card that was not used (ranging from 0 to 48). Both are valid measures of shifting ability in children (Cianchetti et al., 2007).

ACADEMIC ACHIEVEMENT

As a measure of academic achievement, ability scores in mathematics and spelling were derived from the Dutch child academic monitoring system (CAMS; Gillijns & Verhoeven, 1992). Most Dutch primary schools use this system, to keep track of students' progress in academic skills throughout primary education. Twice a year each child is tested on mathematics, reading, and spelling. Raw scores on these tests are converted to a proficiency score and level with a norm table which is based on scores of a large, representative sample of Dutch primary school students. By using these norm scores, a student's performance in one year can be easily compared to scores reached in previous years to see how much progress a child is making (Janssen, & Hickendorff, 2008; Janssen, Verhelst, Engelen, & Scheltens, 2010; de Wijs, Kamphuis, Kleintjes, & Tomesen, 2010).

The *mathematics* test is a valid and reliable (r = .93 to .96) test which is taken individually (Janssen et al., 2010). It measures performance in geometry, number sense and computation, and algebra. The *spelling* test is a valid and reliable (r = .90 to .93) measure of spelling performance and comprises two subtests (de Wijs et al., 2010). The first test is a dictation in which a teacher reads a sentence out loud and repeats a specific word from this sentence. Children were asked to correctly write down this repeated word. In the second test, children were presented with lists of words and from each list they have to recognize the word that was spelled incorrectly.

2.2.3 PROCEDURE

Children were individually tested on the executive functioning tasks by instructed researchers in a quiet room at their own school. Approximately two weeks later, children's muscular strength and aerobic and skill-related fitness were tested during two regular physical education classes. In one lesson the standing broad jump, 10x5m run and plate-tapping test were administered. The 20m shuttle run test was administered in another lesson. Each instructor was familiarized with the executive functioning and physical fitness tests during a training session of two hours. The mathematics and spelling tests were administered by the school at a fixed time point.

2.2.4 DATA SOURCE

This study is based on secondary data-analysis of an existing dataset, coming from an intervention study on the effects of physically active academic lessons on primary school students' physical fitness and cognitive performance. Only data of the pretest of this study was used for the present study, hence ruling out any intervention effects. Several articles were published based on this research project. These studies mainly looked at the effects of an intervention involving physically active academic lessons on physical fitness (de Greeff et al., 2016a; de Greeff et al., 2016b), executive functioning (de Greeff et al., 2016b), academic engagement (Mullender-Wijnsma et al., 2015b), or academic achievement (Mullender-Wijnsma et al., 2015a; Mullender-Wijnsma et al., 2015b, Mullender-Wijnsma et al., 2016; Mullender-Wijnsma, 2017). Furthermore, two other studies have been published using only the pretest data, namely: a study on the relation between physical fitness and academic achievement in children with and without a social disadvantage (de Greeff et al., 2014); and a study on the mediating role of physical fitness in the relationship between socioeconomic status and executive functions (de Greeff, 2016). In none of these studies the relations between physical fitness, executive functioning and academic achievement were examined simultaneously, which is why we wrote the present manuscript.

All executive functioning measures that were used in the original research project were included in the present study as well. Not all measures for academic achievement and physical fitness were used in the present study however. We decided not to use scores on technical reading, as those rely less on executive functioning, but instead are more dependent on phonological decoding and word identification (Sesma, Mahone, Levine, Eason, & Cutting, 2009). Although in the original study scores on arithmetic speed were obtained, it was expected that those would rely less on executive functioning, but rather on arithmetic fact retrieval (van der Sluis, de Jong, & van der Leij, 2007). As such, we decided to only use the general mathematics score.

For physical fitness, we decided not to include the measures of handgrip strength (maximum isometric strength of the hand and forearm muscles) and sit-ups (endurance of the abdominal and hip-flexor muscles), which are both measures of muscular strength. We included one measure per aspect of physical fitness and decided to use the standing broad jump (SBJ) as measure of muscular strength, because it has been found to be strongly related to other measures of upper and lower body strength (Castro-Piñero et al., 2010). The SBJ can therefore be considered a more general index of muscular strength. The measures for abdominal strength (sit-ups) and handgrip strength were expected to be more specific measures reflecting the muscular strength of a specific part of the body.

2.2.5 DATA ANALYSIS

Initial data analyses were conducted in IBM SPSS Statistics 23.0 for Windows. First, data were screened for missing values and outliers. Missing data was observed on one or more variables for 101 of the cases. Little's MCAR test was not significant (χ^2 (82) = 88.01, *p* = .31) suggesting that the data was missing completely at random. Participants were excluded when they had missing values on both of the outcome variables (mathematics and spelling; *N* = 33). For the other 68 cases, full-information maximum likelihood estimation was performed in Mplus 7.31 (Muthén & Muthén, 1998-2006) to estimate missing data by computing a likelihood function for each individual based on available data. FIML is a highly recommended approach to handle missing data (see for example Enders, 2010).

A confirmatory factor analysis (CFA) was conducted in Mplus to see whether the suggested factor structure was a good fit to the data. Two multi-indicator factors were created, one for shifting (with the indicators MWCST efficiency and MWCST preservative errors) and one for physical fitness (with the indicators standing broad jump, 20m shuttle run, 10x5m shuttle run and plate tapping). In addition, three single-indicator factors were created for inhibition (indicated by the Stroop inference score), verbal working memory (indicated by the digit span backward) and visuospatial working memory (indicated by the visual span backward), with their corresponding factor loadings fixed at 1 and indicator error variance (*e*) fixed at the product of the measure's sample variance (VAR(X)) and 1-ρ, where ρ refers to the reliability of the measure (.81 for Stroop inference, .82 for digit span backward, and .75 for visual span backward (see above); Brown, 2006, p. 139). Covariances between verbal working memory, visuospatial working memory and shifting were added because significant correlations between those variables were found in a correlation analysis (see Appendix 1). The factor structure resulted in a good model fit.

This factor structure was consequently used to fit two multilevel structural equation (SEM) models in Mplus using weighted least squares means and variances adjusted (WLSMV) estimation. The conventional Chi-square statistic (χ^2) and related p-value, the root mean square error of approximation (RMSEA), and comparative fit index (CFI) were used as fit indices, with cut-offs of > .05 (p-value), .06 and .90 respectively (Hu & Bentler, 1999). Two models were built in which both academic domains were included as outcome variables: one model with direct relations between physical fitness and executive functioning as predictors of academic achievement level in mathematics and spelling, and a second model in which indirect paths (via executive functioning) were added between physical fitness and academic achievement level in mathematics and spelling.

The outcome variables for academic achievement level were dichotomous variables comparing the lowest performers in mathematics or spelling to their higher achieving peers. Gender and age were entered into all models as covariates and were related to physical fitness, executive functioning and academic achievement because of expected relations between those concepts. Standardized estimates of the path coefficients and corresponding significance values were obtained for significance testing. Direct and indirect effects were obtained using maximum-likelihood, and corresponding standard errors were calculated using the multivariate Delta method (Muthén, 2011).

2.3 RESULTS

Overall mean scores on the cognitive and physical tests and mean scores for the average-to-high achieving and low achieving students in mathematics and spelling separately are presented in Table 2.2.

2.3.1 CONFIRMATORY FACTOR ANALYSIS

Before examining the direct and indirect relations of the structural model, a confirmatory factor analysis was conducted to see whether the factor structure in the measurement model was a good representation of the data. The model with two multi-indicator factors (shifting and physical fitness), three single-indicator factors (verbal working memory, visuospatial working memory and shifting) and covariances between verbal working memory, visuospatial working memory and shifting proved to be a good fit to the data (χ^2 (20) = 45.29, $p = .001$, RMSEA = .05, CFI = .95). Although the χ^2- statistic was below the traditional fit cutoff ($p > .05$), we decided to accept the model as both other fit indices were above their cutoff and as we preferred minimal post-hoc modifications. In addition, the χ^2 is sensitive for sample size, model size and distribution of variables and is therefore not considered very useful by most researchers (Hu & Bentler, 1998).

2.3.2 MAIN ANALYSES

The factor structure tested above was consequently used to test two structural models. In the first model, only direct relations between physical fitness and academic achievement level and between executive functioning and academic achievement level were added to examine whether physical fitness and executive functioning were predictive of academic achievement level in mathematics. The model was not a good fit to the data (χ^2 (48) = 128.05, $p < .001$, RMSEA = .06, CFI = .81) and results were not further interpreted.

TABLE 2.2. Means and standard errors on the physical fitness and executive functioning measures for average-to-high achieving and low achieving students in mathematics and spelling.

		Mathematics		Spelling	
	Total	Average-to-high	Low	Average-to-high	Low
	(n = 477)	(n = 399)	(n = 73)	(n = 421)	(n = 52)
Fitness					
SBJ (cm)	124.4 (1.0)	125.0 (1.1)	120.4 (2.6)	124.2 (1.0)	126.8 (3.3)
Plate tapping (sec) [a]	17.9 (.2)	17.8 (.2)	18.6 (.4)	17.9 (.2)	18.1 (.5)
10x5m SR (sec)[a]	24.5 (.1)	24.3 (.1)	25.7 (.3)	24.5 (.1)	24.6 (.4)
20m SR (n tracks)	31.3 (.7)	31.9 (.8)	27.3 (1.6)	31.5 (.8)	29.9 (2.0)
Cognition					
Inhibition	17.8 (.4)	18.0 (.4)	16.7 (.9)	17.7 (.4)	18.3 (1.0)
VWM (n correct)	5.1 (.1)	5.2 (.1)	4.2 (.2)	5.2 (.1)	4.5 (.2)
VSWM (n correct)	5.7 (.1)	5.9 (.1)	4.2 (.2)	5.7 (.1)	5.4 (.3)
Shifting					
Efficiency	21.4 (.5)	22.2 (.6)	16.6 (1.1)	21.7 (.6)	19.5 (1.4)
Pers. errors (n)[a]	4.5 (.2)	4.1 (.2)	5.7 (.5)	4.2 (.2)	5.3 (.7)

Note: SR = shuttle run, SBJ = standing broad jump VWM = verbal working memory, VSWM = visuospatial working memory.
[a] Lower scores indicate better performance.

The second model with added indirect relations between physical fitness and academic achievement via executive functioning proved to fit the data well (^{2} (39) = 66.19, $p = .004$, RMSEA = .04, CFI = .94). Again the χ^2- statistic was below the traditional fit cutoff ($p > .05$), but as discussed above we decided to accept the model based on the other fit indices. Significant direct relations in the model are presented in Figure 2.1 (the full model including non-significant paths, factor loadings, error terms and covariances can be found in Appendix 2).

The covariates age (ß = .34, $p < .001$, 95% CI: .21 to .47) and gender (ß = .26, $p < .001$, 95% CI: .16 to .36) were significantly related to physical fitness, indicating better performance of older students compared to their younger peers and boys compared to girls.

MATHEMATICS

In total, a significant 51.2% of the variance of the difference between low achievers and average to high achievers in mathematics was explained by the direct and indirect paths with physical fitness and executive functioning, controlling for age and gender ($p < .001$). The total effect from physical fitness to mathematics achievement level was significant (ß = .31, $p < .001$, 95% CI: .14 to .49). The indirect relations between physical fitness and mathematics achievement level via executive functioning accounted for a significant 69.1% of the total effect (ß = .22, $p < .001$, 95% CI: .15 to .29). The direct effect from physical fitness to mathematics achievement level accounted for 30.9% of the total effect, which was not significant (ß = .10, $p = .33$, 95% CI: -.10 to .29).

Direct relations. Verbal working memory (ß = .29, $p = .007$, 95% CI: .08 to .50) and visuospatial working memory (ß = .49, $p < .001$, 95% CI: .29 to .70) significantly predicted categorization in the lowest compared to the higher achievement levels. Children with lower verbal working memory, and visuospatial working memory were more likely to be in the lowest compared to the higher achievement levels. Physical fitness (ß = .10, $p = .33$, 95% CI: -.10 to .29), inhibition (ß = .05, $p = .55$, 95% CI: -.22 to .13) and shifting (ß = .10, $p = .41$, 95% CI: -.19 to .40) were not significant predictors of being in the lowest compared to the higher achievement levels.

*Indirect relations***.** The indirect path between physical fitness and mathematics achievement level via verbal working memory (ß = .06, $p = .03$, 95% CI: .01 to .12) and visuospatial working memory (ß = .12, $p < .001$, 95% CI: .05 to .19) were significant. Lower physical fitness was related to lower verbal and visuospatial working memory, which both significantly differentiated between the lowest and the higher achieving students. There were no significant indirect relations between physical fitness and mathematics achievement level via inhibition (ß = .01, $p = .55$, 95% CI: -.02 to .03) and shifting (ß = .03, $p = .41$, 95% CI: -.04 to .10).

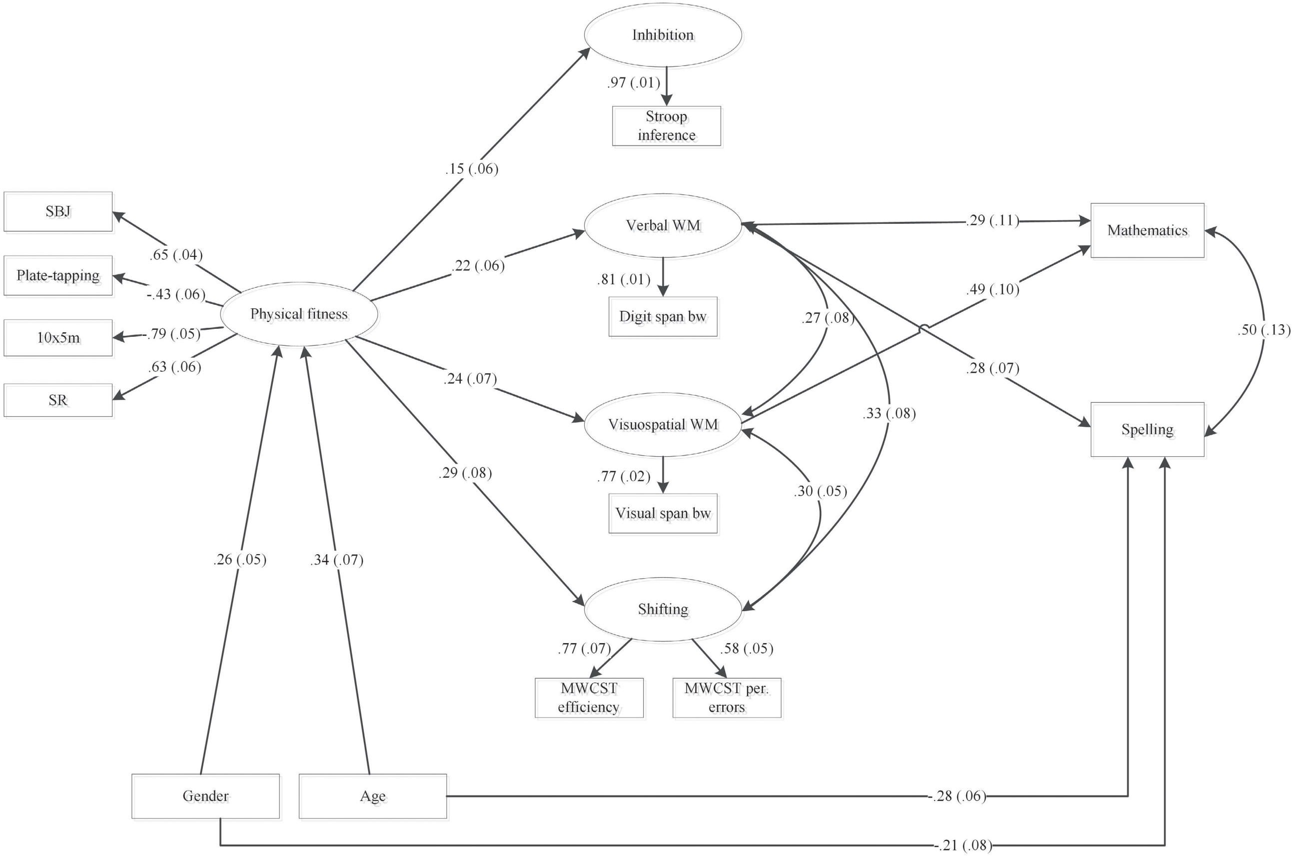

FIGURE 2.1. Significant paths between physical fitness, executive functioning and achievement level (low vs. high) in mathematics and spelling, controlling for gender and age. Standardized path coefficients (ß) and associated standard errors are displayed in the figure.

SPELLING

In total 22.9% of the variance of the difference between low achievers and average-to-high achievers in spelling was explained by the direct and indirect relations with physical fitness and executive functioning, controlling for age and gender ($p < .001$). The total effect from physical fitness to spelling achievement level was not significant (ß = .16, $p = .23$, 95% CI: -.10 to .41). The indirect relations between physical fitness and spelling achievement via executive functioning accounted for a significant 65.4% of the total effect (ß = .10, $p = .02$, 95% CI: .02 to .19). The direct effect from physical fitness to spelling achievement level accounted for 34.6% of the total effect, which was not significant (ß = .06, $p = .69$, 95% CI: -.21 to .32).

Direct relations. Verbal working memory (ß = .29, $p < .001$, 95% CI: .16 to .41) significantly predicted categorization in the lowest compared to the higher achievement levels. Children with lower scores on verbal working memory were more likely to be in the lowest compared to the higher achievement levels. Physical fitness (ß = .06, $p = .69$, 95% CI: -.21 to .32), inhibition (ß = -.04, $p = .55$, 95% CI: -.22 to .13), visuospatial working memory (ß = .07, $p = .71$, 95% CI: -.29 to .43) and shifting (ß = .11, $p = .48$, 95% CI: -.19 to .40) did not significantly predict low spelling achievement level when compared to the higher achievement levels.

Both the covariates age (ß = -.28, $p < .001$, 95% CI: -.40 to -.16) and gender (ß = -.21, $p = .01$, 95% CI: -.37 to -.05) were significantly related to spelling achievement, with girls and younger students performing better compared to boys and older students.

*Indirect relations***.** The indirect path between physical fitness and spelling achievement level via verbal working memory was significant (ß = 0.06, $p = .01$, 95% CI: .01 to .11), indicating that poorer physical fitness was related to poorer verbal working memory, which in turn predicted low spelling achievement. There were no significant indirect paths between physical fitness and spelling achievement via inhibition (ß = -.01, $p = .61$, 95% CI: -.03 to .02), visuospatial working memory (ß = .02, $p = .71$, 95% CI: -.07 to .10) and shifting (ß = .03, $p = .48$, 95% CI: -.05 to .12).

2.4 DISCUSSION

In agreement with previous studies, a positive relation between physical fitness and academic achievement was found in both domains (Fedewa & Ahn, 2011; Santana et al., 2016). Importantly, this relation was not direct, but indirect, via executive functioning. A model with only direct relations between physical fitness and executive functioning on the one hand and low academic achievement on the other hand was not a good fit to the data, showing that physical fitness was not an independent predictor of academic achievement. Rather, in the relation between physical fitness and academic achievement, executive functioning seems to act as a restrictor. Although longitudinal studies are needed to confirm our findings, these results suggest that when physical fitness is used to improve academic achievement, it should first exert positive effects on executive functioning in order to be successful.

2.4.1 MEDIATING RELATIONS

The mediating role of executive functioning in the relation between physical fitness and academic achievement has been found in a previous study as well (van der Niet et al., 2014). Our study extends these results by showing that the mediating role of executive functioning is not general but specific. Verbal working memory was a mediator between physical fitness and low achievement in both domains, whereas visuospatial working memory had a mediating role only in mathematics. An explanation for these specific mediating relations may lay in the different developmental trajectories of the four executive functions, which are caused by the difference in developmental rate of brain areas supporting these executive functions (Olson & Luciana, 2008; Best & Miller, 2010). Inhibition and working memory are thought to develop first, laying the foundations for the development of shifting ability, which is the latest maturing executive function (Best & Miller, 2010; Olson & Luciana, 2008; Purpura, Schmitt, & Ganley, 2017). Although inhibition and working memory start to develop at the same time, the development of working memory is more prolonged, showing growth into late adolescence. Inhibitory performance stabilizes by the early school years and improvements in inhibitory skill do not strongly relate to neural changes after this age (Best & Miller, 2010). Inhibition might therefore not be that sensitive for the influences of physical fitness in the age group that we examined. The development of working memory on the other hand seems to be particularly striking in the age group examined in our study (Best & Miller, 2010), probably making this aspect of executive functioning the most sensitive for influences of physical fitness. As we have shown in this study, verbal working memory in its turn is important for both mathematics and spelling performance, and visuospatial working memory specifically aids mathematics performance.

Alternatively, or additionally, the fact that we found mediating relations only via working memory is in line with previous studies reporting the strongest predicting value of working memory for academic achievement (e.g. Bull & Lee, 2014; van der Ven, Kroesbergen, Boom, & Leseman, 2012). These relations have led to the suggestion that working memory is a common source for both inhibition and shifting, which plays a dominant role and undermines the influences of inhibition and shifting (Bull & Lee, 2014). According to this assumption, only relations between working memory and academic achievement will be significant when inhibition, shifting and working memory are examined simultaneously, which is in accordance with the results of our study. Interestingly, when we analysed academic achievement as a continuous outcome measure (see Appendix 3 for the results), shifting was found to be a significant mediator between physical fitness and academic achievement in both mathematics and spelling. This suggests that shifting is important for academic achievement, but that it is not specifically predictive of low academic achievement.

One important and related issue is the task impurity problem that is associated with executive functioning. Different measures (e.g. for inhibition the Flanker task, Stroop task or Stop-Signal task) and different scores (e.g. Stroop difference score or Stroop inference score) have been used to measure executive functioning in different studies. Further, it has been argued that many of the tasks used to measure inhibition also require involvement of working memory, and tasks used to measure shifting also tap into inhibitory ability and working memory capacity (see Best & Miller, 2010). According to some researchers all tasks require the involvement of working memory to some degree, as it is needed to keep task requirements in mind (Garon, Bryson, & Smith, 2008; van der Ven et al., 2012). This argument could also explain why working memory is often found to be the dominant executive function in the relation with academic achievement. The task impurity problem is an important issue to take into account in future research. It seems useful to include several tasks or scores for each executive function to get a more reliable measure of the true latent ability level of executive functioning. Still, even though in our study we only used one measure for each executive function, we believe that the executive functioning measures used were able to distinguish between students with low and students with higher levels of executive functioning, as we found significant relations between physical fitness and each of the executive functions.

Our results suggest that physical fitness interventions have the potential to improve academic achievement of low achieving students. The mediating effect of executive functioning further suggests that these improvements in academic achievement will be preceded by enhanced executive functions, either verbal working memory (in spelling) or both verbal and visuospatial working memory (in mathematics), although longitudinal or intervention studies are needed to confirm this suggestion. In a world where children are getting increasingly unfit (e.g. Schokker, Visscher, Nooyens, van Baak, & Seidell, 2007), these results are very encouraging as they suggest that physical fitness interventions designed to improve children's physical health can be beneficial for cognition and academic achievement as well.

2.4.2 MODELING RELATIONS IN MATHEMATICS VERSUS SPELLING

The predicting value of physical fitness and executive functioning was much lower in the domain of spelling than in the domain of mathematics, with 22.9% of explained variance in spelling versus 51.2% of explained variance in mathematics. This result coincides with the conclusion mentioned earlier, which stated that the relation between executive functioning and academic performance is especially strong in the domain of mathematics (Bull & Lee, 2014; Cragg & Gilmore, 2014). Also, this finding is in line with results of a meta-analysis reporting that the largest effects of physical activity on children's cognitive outcomes could be found for mathematics achievement (Fedewa & Ahn, 2011). Not only do there seem to be specific relations between physical fitness, executive functioning, and academic achievement level depending on the academic domain involved, but the strength of these relations also seems to differ per domain. Results of our study suggest that improvements in physical fitness will be especially beneficial for achievement in mathematics.

2.4.3 STRENGTHS, LIMITATIONS AND FUTURE DIRECTIONS

Strengths of this study include the large sample size and the examination of specific rather than general relations between physical fitness, executive functioning and academic achievement.

A first limitation of this study is that we were not able to make statements on the causality of our findings as we took a cross-sectional approach. It would be interesting to see whether physical fitness also has causal effects on academic achievement via specific executive functions by means of an experimental designed physical fitness program with clear stimulation of executive functioning in mind.

Secondly, low achievers in mathematics and low achievers in spelling were examined separately in this study. Low achievement often extends beyond one domain however, making children with low achievement in mathematics more likely to be low achievers in spelling as well (Tang, 2007). It would be interesting to see whether the relations that we found for low achievement in mathematics and spelling would also apply in case of simultaneous low achievement in both mathematics and spelling. These students seem to experience an additive combination of the problems that students with a single learning deficit face (van der Sluis et al., 2004), suggesting that a model with a combination of the significant pathways for mathematics and spelling would apply. Unfortunately, we were not able to study this hypothesis due to the low number of students achieving simultaneously low in both mathematics and spelling, but this would be an interesting issue to address in future studies.

Lastly, the sample included in our study was unequally distributed regarding their age, with girls on average being younger than boys. This unequal age distribution can probably also account for the unexpected negative relation that was found between age and spelling achievement, indicating that younger students performed better on the spelling test. Girls generally perform better in spelling (Allred, 1990) and as girls in our study were significantly younger than boys, this could have led to the negative relation between age and spelling. Still, we think our results apply to the general population of primary school students in this age group as the effects of age and gender were controlled for by including them in the model as covariates.

2.4.4 CONCLUSION

Although the mediating effect of executive functioning in the relation between physical fitness and academic achievement has been found before, our study is the first to show that the relation between physical fitness and academic achievement is mediated by specific executive functions, depending on the domain involved. Verbal working memory mediated the relation between physical fitness and low achievement in both domains, whereas visuospatial working memory specifically mediated between physical fitness and low mathematics achievement. Different paths predicted low achievement in mathematics compared to low achievement in spelling, with higher predicting values for mathematics than for spelling. These results suggest that physical fitness interventions could be very successful in improving low academic achievement, especially in mathematics, when they improve executive functions, as these seem to be strongly linked to academic achievement. Intervention studies are needed to show whether improvements in physical fitness can indeed be used to improve academic achievement of low academic achievers. Importantly, these type of physical fitness interventions will have the additional benefit that they exert positive effects on children’s health, physical fitness, and motor development.


3

IMPORTANCE OF AEROBIC FITNESS AND FUNDAMENTAL MOTOR SKILLS FOR ACADEMIC ACHIEVEMENT

This chapter is based on:
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ABSTRACT

Aerobic fitness and fundamental motor skills have both been related to children's academic achievement. Results of studies that have simultaneously related aerobic fitness and fundamental motor skills to academic achievement have provided inconsistent results, and the exact relations with achievement in distinct academic domains remain unknown. The current study examined unique relations between aerobic fitness, fundamental motor skills, and achievement in reading, mathematics and spelling. In total, 891 students (Mean age=9.17 years, *SD* = .66) from 22 primary schools participated. Two multilevel structural equation models were constructed, with relations between aerobic fitness (20m-shuttle run test), fundamental motor skills (tested with items of the Körperkoordinationstest für Kinder and Bruininks-Oseretsky Test for Motor Proficiency) and: (1) overall academic achievement, or; (2) achievement in the domains of reading, mathematics, and spelling (assessed with standardized academic achievement tests). Fundamental motor skills were more strongly related to overall academic achievement than aerobic fitness, but the exact relations differed by academic domain. Aerobic fitness predicted spelling achievement, whereas motor skills predicted reading achievement, and both were predictive of mathematics achievement.

Although more research is needed to disentangle the exact way in which aerobic fitness, motor skills, and academic achievement are linked, the results suggest that children's academic achievement benefits most from engagement in various physical activities that target both aerobic fitness and gross motor skills. These findings emphasize the importance of providing children with opportunities to engage in a wide variety of sports and activities.

3.1 INTRODUCTION

Engagement in regular physical activity is important for children to remain physically active throughout life (Janz, Dawson, & Mahoney, 2000), for their physical fitness and health (see Kohl & Cook, 2013), and for their development of motor skills (Riethmuller, Jones, & Okely, 2009). In recent years, research has also provided evidence for the beneficial effects of physical activity on children's academic performance in primary school (see for example de Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018a; Donnelly et al., 2016; Vazou, Pesce, Lakes, & Smiley-Oyen, 2016). In line with the positive effects of physical activity on academic achievement, studies have shown that fitter children show better academic achievement than their less fit peers (de Bruijn, Hartman, Kostons, Visscher, & Bosker, 2018 [Chapter 2]; Santana et al., 2017), and that children with better developed motor skills generally also perform better at school (Haapala, 2013).

3.1.1 PHYSICAL FITNESS AND ACADEMIC ACHIEVEMENT

Most studies on relations between the physical and cognitive domain have focused on the association between cardiovascular aspects of physical fitness (also termed 'aerobic fitness') and academic achievement. Aerobic fitness refers to the ability to engage in physical activity for a protracted period of time (Caspersen, Powell, & Christenson, 1985). Strong evidence for a positive association between aerobic fitness and academic achievement in both children and adolescents has been provided, with higher levels of aerobic fitness being related to better academic performance (see Santana et al., 2017 for a systematic review). The most consistent relations between aerobic fitness and academic achievement are found in the domain of mathematics (de Bruijn et al., 2018 [Chapter 2], Chaddock-Heyman et al., 2015; Chomitz et al., 2008; Lambourne et al., 2013), although relations have been found for spelling (de Bruijn et al., 2018 [Chapter 2]; Pindus et al., 2016) and reading (Chomitz et al., 2008) as well.

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

3.1.2 FUNDAMENTAL MOTOR SKILLS AND ACADEMIC ACHIEVEMENT

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

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

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

3.1.3 AEROBIC FITNESS VS MOTOR SKILLS

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

In one of the few studies that did examine relations between aerobic fitness, motor skills and academic achievement it was found that both aerobic fitness and motor skills were related to children's (aged 6 – 18 years) academic achievement in reading and mathematics, with stronger relations for motor ability than for cardiorespiratory capacity (standardized coeffients (β) for motor skills ranging from β = .16 to β = .21, and for aerobic fitness ranging from β = .11 to β = .14; Esteban-Cornejo et al., 2014). Studies by Haapala and colleagues (2014), Aadland, and colleagues (2017) found that the unique associations of aerobic fitness and motor skills with academic achievement in primary school differed for boys and girls. Still, despite these gender-specific associations Haapala and colleagues (2014) concluded that motor performance seems to be more important for academic skills than aerobic fitness.

Studies examining the relations of aerobic fitness and motor skills with other aspects of cognition (e.g. working memory and attention; Aadland et al., 2017) have also reported stronger relations between motor skills and cognition than between aerobic fitness and cognition. Although the terms 'cognition' and 'academic achievement' cannot be used interchangeably, as both refer to different concepts, cognitive functions are important predictors of academic performance (e.g. Best, Miller, & Naglieri, 2011; Diamond, 2013), making it likely that they relate to aerobic fitness and motor skills in the same way. It has been suggested that motor skill learning (compared to aerobic activities) more strongly relies on the brain structures and functions also involved in cognition, resulting in stronger relations between motor skills and cognitive performance than between aerobic fitness and cognition (Koutsandréou, Wegner, Niemann, & Budde, 2016; Voelcker-Rehage & Niemann, 2013). In line with this reasoning, a meta-analysis by de Greeff and colleagues (2018a) showed that physical activity interventions focusing on cognitively-engaging physical activity targeting more complex (motor) skills had a moderate-to-large positive effect (ES = .53) on cognitive performance of children in primary school, compared to a small-to-moderate positive effect (ES = .29) for aerobic physical activity programs that aim to target aerobic fitness. In their review and meta-analysis, Vazou and colleagues (2016) reached the same conclusion on the effects of different types of physical activity on cognition in primary school.

3.1.4 DISTINCT ACADEMIC DOMAINS

Besides the hypothesis that aerobic fitness and motor skills are expected to relate differently to academic achievement, it is likely that these relations will differ depending on which academic domain is examined. Mathematics, reading, and spelling are often seen as the core academic domains, because well-developed skills in these domains are critical for performance in other scholastic domains such as geography and history, and for success in children's further career (Onderwijsraad, 2011). The cognitive skills important for mathematics are not the same as those needed for reading and spelling (e.g. de Bruijn et al., 2018 [Chapter 2]; St Clair-Thompson & Gathercole, 2006). Therefore, the extent to which aerobic fitness and motor skills are predictive of performance in those domains will also differ. Some support has been provided for these specific relations, but results are not conclusive. For example, studies have reported positive relations of aerobic fitness with mathematics, but not with reading, whereas others have found the exact opposite (see Donnelly et al., 2016). Little is known about the specific relations between motor skills and academic achievement, but a review by van der Fels and colleagues (2015) has shown that the relations between motor skills and cognitive skills are also more specific rather than general. As academic achievement and cognitive functions such as attention and working memory are closely related (Best et al., 2011), it can be expected that the relation between motor skills and academic achievement will be specific instead of general as well.

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

3.1.5 THE PRESENT STUDY

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

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

3.2 METHODS

3.2.1 PARTICIPANTS

In total, 891 students (451 girls, 50.6%) from 22 primary schools (grades 3 and 4) in the Netherlands participated in this study. Mean age of the participating students was 9.17 years (*SD* = .66), with 51.2% (*n* = 456) drawn from Grade 3 and 48.8% (*n* = 435) from Grade 4. Students had a mean Body Mass Index (BMI) of 16.73 (*SD* = 2.41; based on *n* = 857, because of missing values for 34 (3.8%) students). Based on the classification values by Cole and Lobstein (2012), 724 students (81.3%) had a healthy weight, 109 (12.2%) were overweight, and 24 (2.7%) were obese. Informed consent was provided for all children by their legal guardians. The study was ethically approved by the ethics committee of the Faculty of Behavioral and Movement Sciences at the Vrije Universiteit Amsterdam.

3.2.2 MATERIALS

AEROBIC FITNESS

Shuttle Run Test. The 20m Shuttle Run Test of the Eurofit physical fitness test battery (van Mechelen, van Lier, Hlobil, Crolla, & Kemper, 1991) was administered as a measure of cardiovascular endurance, which was used as indicator of aerobic fitness. In this test, children ran back and forth between two lines that were 20m apart within a specific time interval that was indicated by audio signals. The interval between each successive signal became smaller as the test proceeded. The test ended when a child failed to reach a line prior to the signal on two successive trials. The number of completed tracks (i.e. the number of times a child had run back and forth) was used as a score of aerobic endurance. The Shuttle Run Test is considered a reliable (test-retest reliability $r = .89$; Leger, Mercier, Gadoury, & Lambert, 1988) and valid measure of children's aerobic fitness (Leger et al., 1988; Voss, & Sandercock, 2009), and is the most appropriate test of aerobic fitness in children and adolescents (Artero et al., 2011).

FUNDAMENTAL MOTOR SKILLS

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

Eye-hand coordination (BOT-II). The upper-limb coordination subtest of the BOT-II was used to measure eye-hand coordination. This subtest consists of seven tasks, such as bouncing and catching a ball, and catching a tossed ball with both hands. A total score for eye-hand coordination was computed by summing the number of points on the seven tasks. For each task, a total number of five (for five tasks) or seven (for two tasks) points could be reached, resulting in a maximum total score of 39 points. The BOT-II is a reliable (test-retest reliability is .80) and valid test for assessing motor proficiency in children (Deitz, Kartin & Kopp, 2007).

Locomotor skills (KTK). Children's level of locomotor skill was established with two subtests of the KTK: shifting platforms and jumping laterally. In the shifting platforms test a child stood with both feet on a platform (25cm x 25cm) which was supported by four legs of 3.7cm in height. The child was then asked to place a second identical platform alongside the first one using both hands. The child stepped on this second platform, replaced the first platform in the same manner and stepped upon this newly placed platform again. A child was awarded two points for each successful transfer from one platform to the next: one point for shifting the platform and one point for transferring the body. A total score was calculated by summing the number of points of two trials of 20s. Test-retest reliability of the shifting platforms subtest is .85 (Kiphard & Schilling, 1974; 2007).

In the jumping laterally test a child stood on a mat with a wooden slate in the middle and made consecutive jumps from side to side over the slate as quickly as possible. Each child got two attempts to make as many jumps as possible within 15 seconds. The total number of correct jumps in the two trials together was recorded as total score. Test-retest reliability of the jumping laterally subtest is good ($\alpha = .95$; Kiphard & Schilling, 1974; 2007).

Balance (KTK). The balance subtest of the KTK was used to measure children's balancing skills. In the balance subtest, a child walked backwards on three 3m long balance beams with decreasing widths of 6, 4.5 and 3cm. For each balance beam, a child got three attempts to make as many steps backwards as possible (with a maximum of eight). The number of successful steps per attempt was recorded. Each attempt had a maximum score of eight steps, leading to a maximum score of 24 steps per balance beam, and a total maximum score of 72 for the three beams together. The balance subtest is a valid and reliable measure of children's balancing skills (test-retest reliability is .80; Kiphard & Schilling, 1974; 2007).

The KTK is a reliable (test-retest reliability $\alpha = .97$) and valid measure of motor coordination in children of 5 to 15 years (Kiphard & Schilling, 1974; 2007). The KTK originally consisted of four subtests, but the fourth subtest (hopping for height) was not included in the present study due to time constraints. A previous study has demonstrated that this shorter version of the KTK shows substantial agreement with the original four subtest KTK ($r = .97$; Novak et al., 2017).

ACADEMIC ACHIEVEMENT

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

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

The mathematics test consisted of 20 questions measuring general mathematics ability in the following domains: number sense, arithmetic, knowledge on fractions and ratios, geometry, time and money, and knowledge of charts and figures. Assignments included both basic arithmetic exercises as well as mathematical problems that had to be extracted by the child itself from the information provided in a short text. The mathematics test has demonstrated acceptable reliability (test-retest reliability > .90) and valid measure of children's mathematics ability (Hop, Janssen, & Engelen, 2016).

The spelling test consisted of a dictation in which the teacher read aloud a sentence and repeated one word out of that sentence, which children had to correctly write down. The test consisted of 25 words, resulting in a maximum score of 25. Reliability (test-retest reliability > .90) and content and construct validity of the spelling test are good (Tomesen, Wouda, & Horsels, 2016b).

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

The reading test is a valid and reliable (r = .85) measure of reading comprehension (Feenstra, Kamphuis, Kleintjes, & Krom, 2010). The reading test measures reading comprehension, interpretation of written texts, looking up of information and summarization of written texts.

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

The spelling test is a valid and reliable (r = .88 to .91) test consisting of two parts (de Wijs, Kamphuis, Kleintjes, & Tomesen, 2010). The first subtest is a dictation in which the teacher reads a sentence aloud and repeats one word out of that sentence. Children have to correctly write down this specific word. The second part is a multiple choice test in which children have to identify which word out of a list of words is spelled incorrectly.

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

3.2.3 PROCEDURE

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

3.2.4 ANALYSES

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

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

To analyze the independent associations between aerobic fitness, motor skills, and academic achievement, structural equation (SEM) models were built in Mplus using weighted least squares means and variances adjusted (WLSMV) estimation. The root mean square error of approximation (RMSEA), comparative fit index (CFI), and Tucker-Lewis index (TLI) were used as fit indices, with cut-offs of .06, .90, and .90 respectively (Hu & Bentler, 1998). The conventional Chi-square statistic (χ^2) is reported as well, but was not used for assessing model fit, as it is sensitive for model size, sample size, and distribution of variables (Hu & Bentler, 1998).

Aerobic fitness and fundamental motor skills were used as predictors of the outcome variables academic achievement in mathematics, reading and spelling. One single-indicator latent variable was constructed for aerobic fitness (as indicated by shuttle run test scores), with the corresponding factor loading fixed at 1 and indicator variance (e) fixed at the product of the measure's sample variance [VAR(x)] and $1 - \rho$, where ρ represents the reliability of the test (.80, see above; Brown, 2006, p. 139). A latent factor was constructed to represent fundamental motor skills, made-up out of the four tests for motor skills: ball skills, jumping laterally, shifting platforms, and balance. Three latent variables were constructed for academic achievement, one for each domain, all made up out of the two academic achievement measures: the standardized tests and the school-based measures (CAMS-scores). Age, gender, and BMI were included as covariates and were related to aerobic fitness and motor skills, and the three academic achievement outcome measures. Age and gender were further related to BMI. Covariances between motor skills and aerobic fitness and between the three academic domains were added, as relations between those variables were expected based on theoretical considerations. Standardized estimates of path coefficients (β-values) and corresponding p-values were obtained for significance testing.

3.3 RESULTS

Mean scores on the tests for aerobic fitness, motor skills, and academic achievement are presented in Table 3.1. Correlations between included variables are presented in Table 3.2.

TABLE 3.1. Means, standard deviations and score range on the physical and academic achievement tests.

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

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

3.3.1 CONFIRMATORY FACTOR ANALYSIS

Before the relations in the structural model were examined, a confirmatory factor analysis was conducted to test whether the theoretical measurement model was a good representation of the data. The model with a single-indicator factor for aerobic fitness, a multi-indicator factor for motor skills, three multi-indicator factors for academic achievement, and added covariances between motor skills and aerobic fitness, and between the three academic domains proved to have an acceptable fit to the data ($\chi^2(35) = 65.11$, RMSEA = .03, CFI = .98, TLI = .98). Correlations between the latent variables in this model are presented in Table 3.3.

TABLE 3.2. Bivariate correlations between manifest variables included in the SEM-models.

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

Note * < .05 ** < .01 *** < .001; all variables (except for gender) are standardized based on grade means and SD's; stand., standardized; CAMS, Child Academic Monitoring System; SRT, = Shuttle Run Test; BMI, Body Mass Index

TABLE 3.3. Correlations between latent variables included in the SEM-models.

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

Note: * < .05 ** < .01 *** < .001

3.3.2 MAIN ANALYSES

The measurement model tested above was consequently used to measure the relations in the structural model. First, aerobic fitness and motor skills were used as predictors of overall academic achievement, that is: one multi-indicator higher-order factor with the latent variables for reading, mathematics, and spelling as indicators. This model proved to fit the data acceptably (χ^2 (63) = 237.09, RMSEA = .06, CFI = .92, TLI = .89). Significant paths in the model are presented in Figure 3.1. (The full model including non-significant paths, factor loadings, error terms, and covariances can be found in Appendix 4).

A significant 15.8% of the variance in academic achievement was explained by aerobic fitness and motor skills, controlling for age, gender and BMI ($p < .001$). Motor skills were significant predictors of academic achievement ($\beta = .14$, $p = .024$, 95% CI: .02 to .22) indicating that children with better-developed motor skills also performed better at school. The relation between aerobic fitness and academic achievement was not significant ($\beta = .12$, $p = .057$, 95% CI: -.003 to .23). The covariates age ($\beta = -.34$, $p < .001$, 95% CI: -.40 to -.28) and gender ($\beta = .11$, $p = .029$, 95% CI: .01 to .18) were significantly related to academic achievement, showing that younger students (within a grade level) and girls had a higher academic performance compared to boys and older students. BMI was not significantly related to academic achievement ($\beta = -.01$, $p = .84$, 95% CI: -.08 to .05).

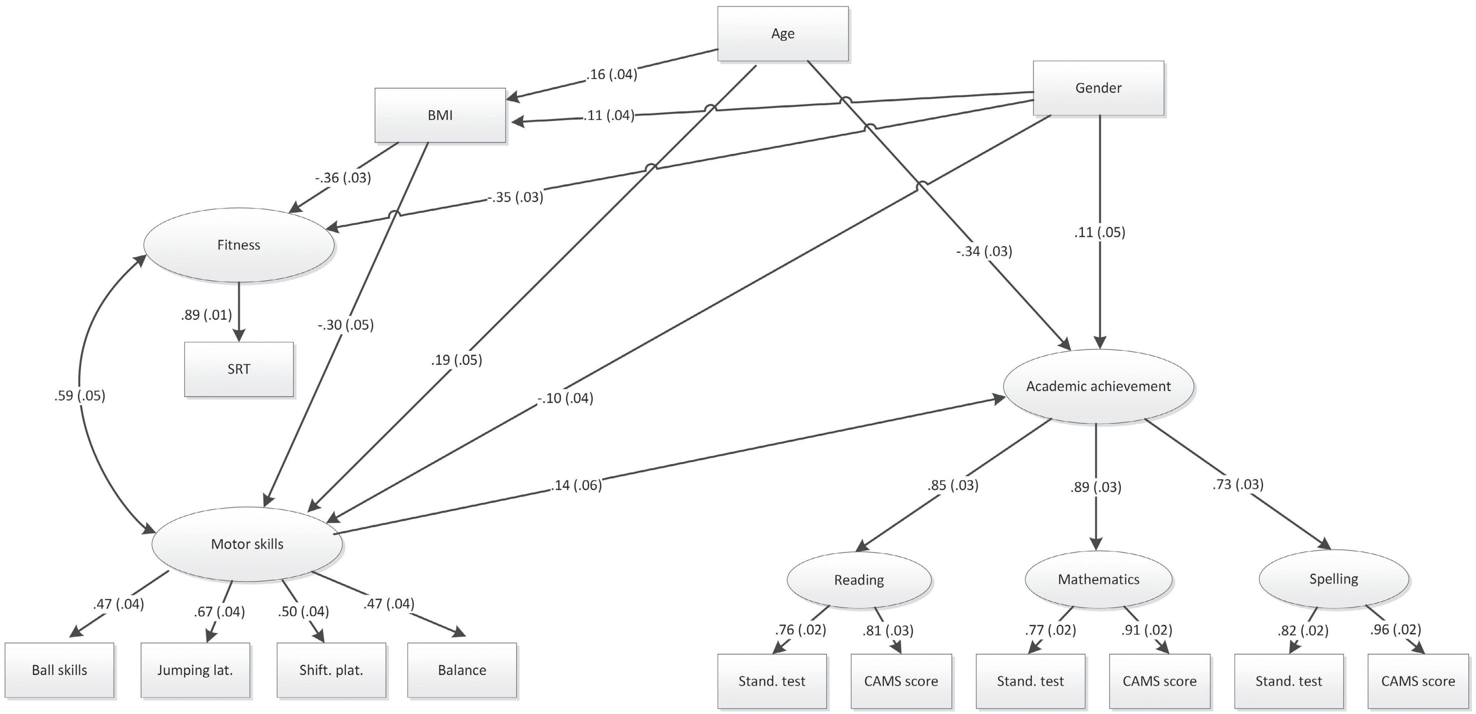

FIGURE 3.1. Significant paths among aerobic fitness, motor skills, and overall academic achievement, controlling for gender, age, and BMI. Standardized path coefficients (betas) and associated standard errors are presented in the figure. Note: SRT, Shuttle Run Test; lat., laterally; shift. plat., shifting platforms; BMI, Body Mass Index; Stand., standardized; CAMS, Child Academic Monitoring System.

SEPARATE ACADEMIC DOMAINS

Next, academic achievement was separated into the three different domains, i.e. reading, mathematics, and spelling, to examine whether the relations between aerobic fitness and motor skills and academic achievement were specific for each domain. This model proved to have an acceptable fit to the data (χ^2 (53) = 161.05, RMSEA = .05, CFI = .95, TLI = .92). Significant relations in the model are presented in Figure 3.2. The χ^2-difference test indicated that this second model including the three academic domains separately had a better fit than the first model where academic achievement was represented as one overall factor (χ^2-difference (10) = 95.93, $p < .001$).

Reading. A significant 11.1% ($p < .001$) of the variance in reading performance was explained by the relation with motor skills ($\beta = .14$, $p = .04$, 95% CI: .01 to .25), controlling for age, gender and BMI. Children with better-developed motor skills were more likely to perform better in reading as well, compared to their peers with less well-developed motor skills. Aerobic fitness was not a significant predictor of achievement in reading ($\beta = .03$, $p = .66$, 95% CI: -.10 to .13). The covariates gender ($\beta = .18$, $p < .001$, 95% CI: .10 to .26) and age ($\beta = -.34$, $p < .001$, 95% CI: -.35 to -.18) were significantly related to reading achievement, indicating that girls and younger students (within a grade level) had better reading performance than boys and older students. BMI was not significantly related to reading achievement ($\beta = -.03$, $p = .41$, 95% CI: -.10 to .03)

Mathematics. A significant 18.9% ($p < .001$) of the variance in mathematics performance was explained by the relationship between aerobic fitness ($\beta = .16$, $p = .017$, 95% CI: .03 to .27) and motor skills ($\beta = .14$, $p = .021$, 95% CI: .02 to .25), controlling for age, gender and BMI ($p < .001$). Students with better-developed motor skills and higher levels of aerobic fitness also performed better in the domain of mathematics. Wald test showed that the path coefficients of aerobic fitness and motor skills did not significantly differ (χ^2 (1) = .66, $p = .42$), indicating that aerobic fitness and motor skills were equally strong predictors of mathematics achievement. The covariates gender ($\beta = -.12$, $p = .01$, 95% CI: -.21 to -.03) and age ($\beta = -.34$, $p < .001$, 95% CI: -.41 to -.27) were significantly related to mathematics performance, indicating that boys and younger students (within a grade level) performed better in mathematics. BMI was not significantly related to mathematic achievement ($\beta = .02$, $p = .58$, 95% CI: -.06 to .10).

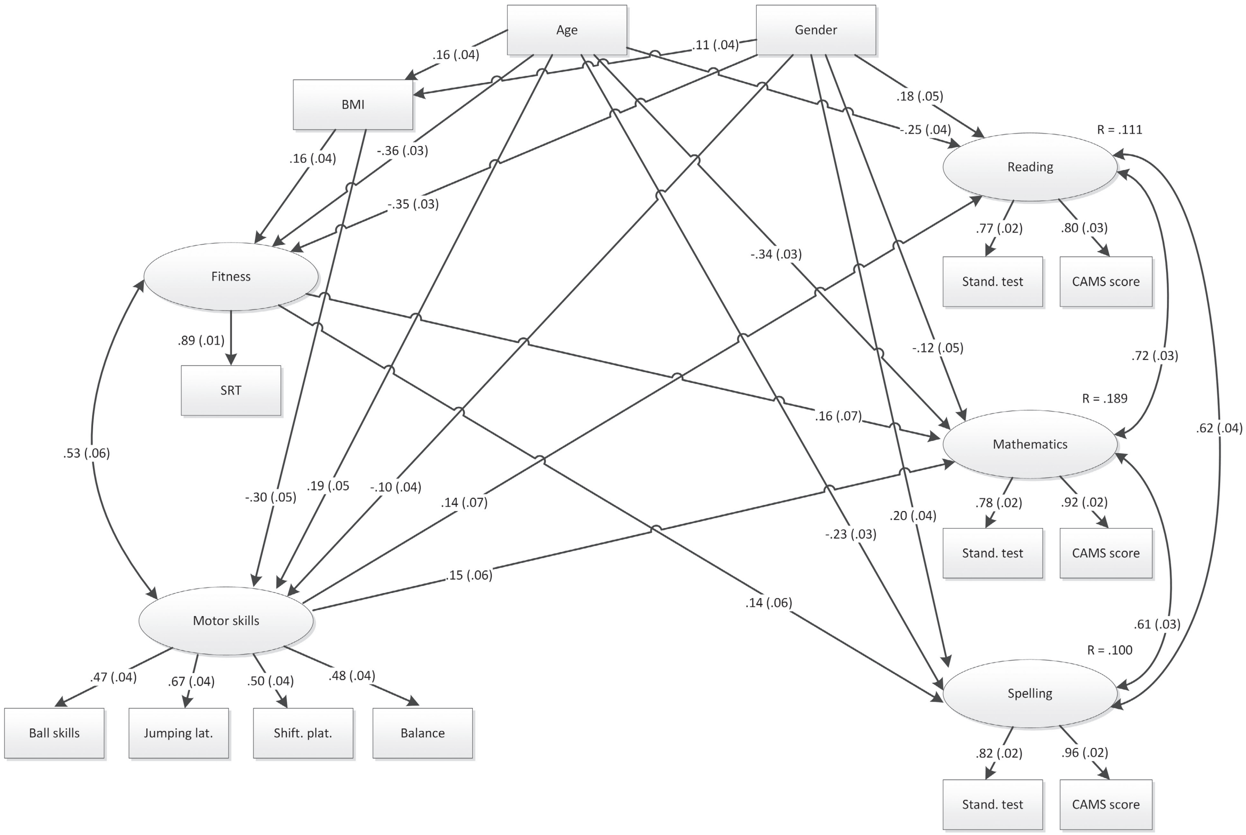

FIGURE 3.2. Significant paths among aerobic fitness, motor skills, and academic achievement in reading, mathematics, and spelling, controlling for gender, age, and BMI. Standardized path coefficients (betas) and associated standard errors are presented in the figure. Note: BMI, Body Mass Index; SRT, Shuttle Run Test; lat., laterally; shift. plat., shifting platforms; Stand., standardized; CAMS, Child Academic Monitoring System.

Spelling. A significant 10.0% ($p < .001$) of the variance in spelling performance was explained by the relation with aerobic fitness ($\beta = .14$, $p = .04$, 95% CI: .01 to .25), controlling for age, gender, and BMI, showing that children who had higher levels of aerobic fitness also performed better in spelling. Motor skills was not a significant predictor of spelling achievement ($\beta = .019$, $p = .75$, 95% CI: -.10 to .11). The covariates gender ($\beta = .20$, $p < .001$, 95% CI: .11 to .29) and age ($\beta = -.23$, $p < .001$, 95% CI: -.29 to -.16) were significantly related to spelling achievement, with girls and younger students (within a grade level) performing better in spelling. BMI was not significantly related to spelling achievement ($\beta = -.01$, $p = .82$, 95% CI: -.08 to .06).

3.4 DISCUSSION

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

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

3.4.1 SPECIFIC RELATIONS

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

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

3.4.2 EXPLANATORY MECHANISMS

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

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

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

3.4.3 STRENGTHS AND LIMITATIONS

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

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

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

3.4.4 CONCLUSION

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


4

VISUOSPATIAL WORKING MEMORY RELATED BRAIN ACTIVATION AND ITS RELATION WITH GROSS MOTOR SKILLS AND AEROBIC FITNESS IN 8-10 YEAR OLD CHILDREN*

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* This chapter has shared first authorship with I. M. J. van der Fels. Both authors have equally contributed to this chapter, order of authors is alphabetically.

ABSTRACT

Relations between visuospatial working memory (VSWM) performance and cardiovascular fitness and/or motor skills in children are explained by underlying brain activation patterns. However, there is no experimental evidence supporting this mechanism, and there is little knowledge on VSWM-related brain activation patterns in children. Therefore, this study aimed to investigate 1) VSWM-related brain activation in 8-10 year-old typically developing children; 2) differences in brain activation depending on task complexity (working memory load); and 3) how VSWM-related brain activation patterns relate to either gross motor skills and/or cardiovascular fitness. Functional Magnetic Resonance Imaging (fMRI) data obtained during a VSWM task was analyzed for 80 children from grade 3 (47.5%) and grade 4 of 21 primary schools in the Netherlands (51.3% girls). Gross motor skills were assessed using three items of the Körper Koordinationstest für Kinder (KTK) and one item of the Bruininks-Oseretsky test of Motor Proficiency, Second Edition (BOT-2). Cardiovascular fitness was assessed using the 20-meter Shuttle Run Test. VSWM-related brain activation was found in the angular gyrus (right hemisphere), the superior parietal cortex (bilateral) and the thalamus (bilateral), and VSWM-related deactivation was found in the inferior and middle temporal gyri (bilateral). There were no significant activation differences between low and high working memory load trials. Gross motor skills and cardiovascular fitness were not related to VSWM-related brain activation, whereas behavioral results showed significant relations between VSWM performance and gross motor skills and cardiovascular fitness. We could not confirm the hypothesis that brain activation patterns underlie the relation between VSWM performance and gross motor skills and/or cardiovascular fitness.

4.1 INTRODUCTION

The childhood years are critical years for the development of cognitive functions, gross motor skills and cardiovascular fitness. One important aspect of cognition is visuospatial working memory (VSWM), the ability to maintain and manipulate visuospatial information over brief periods of time (Baddeley & Hitch, 1994). VSWM is a prerequisite for several cognitive processes such as logical reasoning, problem solving, and academic performance, in particular mathematics (e.g. Baddeley & Hitch, 1974; Baddeley & Hitch, 1994; de Bruijn, Hartman, Kostons, Visscher, & Bosker, 2018 [Chapter 2]; Diamond, 2013). The development of VSWM during childhood is thought to be highly related to maturation of the prefrontal cortex (Dempster, 1992; Diamond, 2013; Goldman-Rakic, 2011).

There is evidence that cognition is related to gross motor skills and cardiovascular fitness (Haapala, 2013; van der Fels et al., 2015). Gross motor skills represent the involvement of large body muscles in balance, limb, and trunk movements (Corbin, Pangrazi, & Franks, 2000). Gross motor skills that children acquire during childhood lead to possibilities to further develop complex movement and sport-specific skills (Clark & Metcalfe, 2002). Well-developed gross motor skills also go hand in hand with higher levels of physical activity, which is important for developing higher levels of cardiovascular fitness. Cardiovascular fitness refers to the ability of the circulatory and respiratory systems to supply oxygen during sustained physical activity (Corbin et al., 2000). Well-developed gross motor skills and adequate levels of cardiovascular fitness are thus not only important for many indicators of health (e.g. blood pressure, overweight and obesity, and cholesterol levels; Janssen & LeBlanc, 2010), but also for cognition. Underlying functional brain mechanisms are thought to be responsible for these positive relations between the physical and cognitive domain. However, little is known about how gross motor skills and cardiovascular fitness are related to VSWM-related brain activation, and how brain activation patterns can explain associations between VSWM and physical capabilities. A better understanding of these relations seems vital, as this can help in developing physical activity interventions that can target both children's physical and their cognitive development.

4.1.1 VSWM-RELATED BRAIN ACTIVATION

Some early animal studies have shown that the dorsolateral prefrontal cortex is an important brain area involved in VSWM performance (e.g. Wilson, Scalaidhe, & Goldman-Rakic, 1993). This finding was later confirmed in functional neuroimaging studies in children and adults, in which VSWM-related brain activation was mainly found in parietal and frontal brain areas, including the posterior frontal gyrus (van Ewijk et al., 2015), the middle frontal gyrus (Kwon, Reiss, & Menon, 2002; Nelson et al., 2000; van Ewijk et al., 2015), the superior frontal gyrus (Kwon et al., 2002; Nelson et al., 2000), the superior parietal cortex (Kwon et al., 2002; Nelson et al., 2000; van Ewijk et al., 2015), the inferior parietal cortex (Nelson et al., 2000), and in the occipital cortex (Nelson et al., 2000; van Ewijk et al., 2015), the premotor cortex (Kwon et al., 2002), the cingulate cortex (Nelson et al., 2000), the cerebellum, thalamus, and insula (van Ewijk et al., 2015). The brain areas that have shown to be involved in VSWM tasks are presented in Figure 4.1.

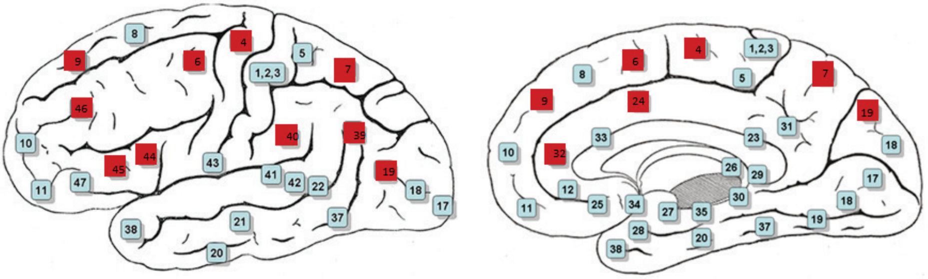


FIGURE 4.1. Overview of Brodmann Areas in red that have been shown to be related to VSWM (Figure based on Gray, 1918). Blue boxes represent all other Brodmann Areas, which have not been related to VSWM. Lateral (left) and medial (right) surfaces are shown.

4.1.2 VSWM AND GROSS MOTOR SKILLS

Positive relations between gross motor skills and VSWM performance have been found in children (de Bruijn et al., 2018 [Chapter 2]; Rigoli, Piek, Kane, & Oosterlaan, 2012b; van der Fels et al., subm.). It is hypothesized that underlying brain mechanisms can explain these relations, because cortical regions involved in VSWM tasks are important brain areas for the planning, execution, and control of movements as well (Goldberg, 1985). It has been shown that the dorsolateral prefrontal cortex, important for VSWM, is involved in a neural circuit with brain regions that are more directly involved in gross motor skills, such as the supplementary motor area and the premotor cortex (Dum & Strick, 1991; Künzle, 1978; Tanji, 1994; Wiesendanger, 1981). Moreover, spatial orientation and the ability to hold information in mind and mentally work with it, both important abilities for VSWM, are also important capacities for skilled gross motor performance. Therefore, it is expected that brain areas that are activated during VSWM tasks are important areas for gross motor skill performance as well (Diamond, 2000). We are not aware of studies investigating relations between gross motor skills and VSWM-related brain activation, leaving this hypothesis unexplored. Further examination of these relations is important, as this will show whether and how physical activity interventions focusing on motor skill development can improve children's VSWM performance as well.

4.1.3 VSWM AND CARDIOVASCULAR FITNESS

Not only gross motor skills, but also cardiovascular fitness has been related to VSWM (de Bruijn et al., 2018; Scudder et al., 2014). To explain the relation between cardiovascular fitness and executive functioning, the cardiovascular fitness hypothesis has been brought forth. This hypothesis states that improved cardiovascular fitness through physical activity mediates effects of physical activity on executive functioning. Participation in physical activity is assumed to lead to changes in the body (physical fitness), which go hand in hand with changes in the brain (e.g. cerebral structure and function, and increases in the release of neurotransmitters), in turn leading to better cognitive performance on, amongst others, executive function tasks (Etnier et al., 1997). This hypothesis is mainly supported by neuroimaging studies investigating relations between cardiovascular fitness and brain activation during interference control tasks. Interference control refers to the ability to cognitively suppress conflicting stimuli (Nigg, 2000). For example, an fMRI study by Chaddock and colleagues (2012) investigated the association between cardiovascular fitness and brain activation during interference control, measured with a Flanker task, in preadolescent children. It was found that during incongruent (i.e. more complex) trials in early tasks blocks, children with higher cardiovascular fitness showed greater activation of the prefrontal and parietal cortex than children with lower cardiovascular fitness. In addition, only children with higher cardiovascular fitness showed a decrease in activity in the prefrontal and parietal cortex across the experimental blocks while maintaining high levels of accuracy, reflecting more efficient use of those brain areas. A study by Voss and colleagues (2011) showed that children with higher cardiovascular fitness had less frontal, temporal, and parietal activity and higher accuracy during incongruent Flanker trials, compared to children with lower cardiovascular fitness. The findings by Chaddock and colleagues (2012) and Voss and colleagues (2011) support the hypothesis that cardiovascular fitness is related to cognitive performance in children, and that differences in brain activation underlie these associations. However, as both of these studies focused on interference control, more research is needed to investigate whether cardiovascular fitness is also related to VSWM-related brain activation, since different brain regions provide distinct contributions to VSWM and interference control (Mecklinger, Weber, Gunter, & Engle, 2003).

4.1.4 THE PRESENT STUDY

The first aim of the present study is to describe VSWM-related brain activation in 8-10 year-old typically developing children. Second, it will be investigated whether there is a difference in brain activation depending on task complexity (i.e. working memory load). Third, it is examined how VSWM-related brain activation patterns are related to either gross motor skills and/or cardiovascular fitness. To clarify the hypothesis that brain activation is the mechanism underlying the relation between gross motor skills and cardiovascular fitness with VSWM, the relation between gross motor skills and cardiovascular fitness with behavioral VSWM performance during scanning is also reported. Based on previous research, VWSM related brain activation is expected mainly in frontal and parietal areas (Kown et al., 2002; Nelson et al., 2000; van Ewijk et al., 2015). Furthermore, it is hypothesized that both gross motor skills and cardiovascular fitness are associated with VSWM performance and VWSM related brain activation. Results of this study will greatly increase our understanding of the relations between physical capacities and VSWM, which will help in the development of physical activity interventions that can target both children's physical, and their cognitive development.

4.2 METHODS

4.2.1 PARTICIPANTS

A total of 92 children from 21 schools in the Netherlands were included in this study (47 girls, 51.1%). Participating children were in grade 3 (*n* = 46, 50.0%) or grade 4, and were 8-10 years old (Mean age = 9.14 years, *SD* = .63). This study was part of a large cluster randomized controlled trial (RCT; '*Learning by Moving*') assessing the effects of two types of physical activity on cardiovascular fitness, motor skills, cognitive functions, and academic performance. Children who participated in the cluster RCT were invited to participate in this MRI sub-study. Only children aged over 8 years that had no contraindications for MRI were included. Written informed consent was provided by children's parents or legal guardians. This study was approved by the ethical board of the Vrije Universiteit Amsterdam (VCWE-S-15-00197) and registered in the Netherlands Trial Register (NL5194).

4.2.2 MATERIALS

IMAGING TASK

An adapted version of a spatial span task developed by Klingberg, Forssberg and Westerberg (2002) was used to assess VSWM (van Ewijk et al., 2014; van Ewijk et al., 2015). The task was created in E-prime (version 2.0.10.356; Psychology Software Tools). A 4 x 4 grid was presented on a screen behind the MRI scanner that was visible for the child via a mirror attached to the head coil. In the grid, a sequence of either three (low memory load) or five (high memory load), either yellow (working memory condition) or red (control condition) circles was presented, 500 ms per circle, with an inter-stimulus interval of 500 ms (Figure 4.2). Next, a probe was presented in one of the 16 possible locations in the grid, consisting of a number, referring to one of the presented stimuli, followed by a question mark. In the working memory conditions, children were instructed to remember the order in which the circles (three or five) were presented. When the probe was shown, the child had to indicate with a right ('yes') or left ('no') button press whether the probe location matched the location of the stimulus that was indicated by the probe number (see example in Figure 4.2). Children were asked to respond within a 2000 ms response window. In the control conditions, the circles (three or five) were shown in a predictable manner in the four corners of the grid, and were always followed by a probe with the number 8. Children were instructed to look at the circles, but not to remember the order, and to always press 'no' when the probe appeared. Feedback was provided in both conditions by presenting a green (correct response) or red (incorrect response) coloured bar underneath the probe. The task was administered in four blocks, each containing 24 trials, with a short break in between blocks, resulting in a total task duration of approximately 16 minutes. The percentage of the correct working memory trials (for the low and high working memory load trials separately, and for the low and high working memory load trials combined) were used as outcome measures for behavioral performance. Figure 4.2 shows a schematic overview of the spatial span task.

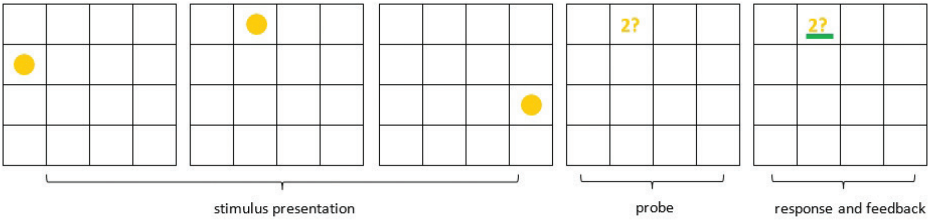


FIGURE 4.2. Schematic overview of a low working memory load trial of the spatial span task. Taken from van Ewijk et al. (2015). In this example trial, a sequence of three (low load) yellow (working memory) circles were presented for 500ms each, with a 500ms inter-stimulus interval (stimulus presentation). Following, a probe appeared, in this example asking whether the second circle appeared on that position in the grid. Children were asked to respond within a 2000 ms response window, in this case answering with 'yes' (the second circle was in that position). The response was followed by feedback (a red or green bar underneath the probe) which was presented for the remainder of the response window (response and feedback). In this example, a correct response ('yes') was given and a green bar appeared below the probe as feedback.

GROSS MOTOR SKILLS

Gross motor skills were evaluated using three subtests (jumping sideways, moving sideways, and backwards balancing) of the Korper Koordinationstest für Kinder (KTK; Kiphard & Schilling, 2007). The KTK originally consists of four subtests, but a recent study has shown substantial agreement between the test battery consisting of three subtests and the original test battery consisting of four subtests (Novak et al., 2017). Additionally, one item of the Bruininks-Oseretsky Test of Motor Proficiency, Second Edition (BOT-2; Bruininks & Bruininks, 2005) was used to measure ball skills. Both test batteries have shown to be reliable and valid for primary school children (Bruininks, 2005; Bruininks & Bruininks, 2005; Kiphard & Schilling, 2007; Novak et al., 2017).

Jumping sideways (KTK). Children jumped laterally as quickly as possible over a small wooden slat (60 x 4 x 2 cm) for 15 s. The total number of jumps in two trials was used as the score for jumping sideways.

Moving sideways (KTK). Children moved across the floor as quickly as possible in 20 s by stepping on, and transferring two plates (25 x 25 x 5.7 cm). Children stepped from the first plate to the next, subsequently lifting and transferring the first plate alongside the second and stepping on it. Each successful transfer from one plate to the next resulted in two points: one for shifting the plate and one for stepping on the next plate. The total number of points on two trials was used as a score for moving sideways.

Backwards balancing (KTK). Children made as many steps backwards as possible on three wooden beams with lengths of 3 m, but decreasing in width (resp. 6 cm, 4.5 cm, and 3 cm). For each beam, children performed three trials. A maximum of eight steps per trial was counted, resulting in a maximum score of 72.

Ball skills (BOT-2). The ball skills subtest consisted of seven activities executed with a tennis ball. Activities were catching, throwing and dribbling a ball with one or both hands and throwing a ball at a target. For each task, five or seven trials were performed. For each correct trial, a child received one point. resulting in a maximum score of 39 points.

CARDIOVASCULAR FITNESS

Cardiovascular fitness was administered with the 20-meter Shuttle Run Test (20-m SRT, in number of completed stages; Adam, Klissouras, Ravazzolo, Renson, & Tuxworth, 1988). In the 20-m SRT, children run back and forth over a distance of 20 meters. An audio signal sounds at the moment children have to touch the line with one of their feet. The starting speed is 8 km/h and every minute, speed increases by 0.5 km/h. The test was terminated when the child failed to reach the end line in time on two consecutive occasions, or due to self-reported fatigue. Validity and reliability of the SRT have shown to be adequate in children (Leger, Mercier, Gadoury, & Lambert, 1988).

4.2.3 PROCEDURE

VSWM was assessed during a functional MRI scan, carried out as part of a scanning protocol that was performed at VU University Medical Centre in Amsterdam (n = 47), or at the University Medical Center in Groningen (n = 45). Children were familiarized with the scanner, using a mock scanner, and with the task in a half hour session prior to the real scanning. Children responded to the task using a button-box (Current designs Inc., Philadelphia, USA). Head movements were minimized by inserting small, wedge-formed pillows between the head coil and the child's head. Children received a small present and a copy of their structural T1-weighted scan.

Cardiovascular fitness and motor skills were assessed by trained research assistants using standardized protocols, at the children's own school, within a time frame of two weeks around the scanning procedure. Cardiovascular fitness was assessed during a physical education lesson in groups of up to 15 children. Motor skills were individually assessed during one or two (depending on the class size) physical education lessons, in circuit form, with tests administered in a random order.

4.2.4 IMAGE ACQUISITION

The imaging protocol was carried out at two different sites (Amsterdam and Groningen) on either a 3 Tesla whole-body unit (Discovery MR750, GE Healthcare, Milwaukee, Wisconsin; Amsterdam) or a 3 Tesla Philips Intera scanner (Philips Medical Systems, Best, the Netherlands; Groningen), using a 32-channel head coil and closely-matched acquisition parameters. Four runs with T2*-weighted functional gradient echo-planar images (EPI) were acquired using the following parameters: repetition time (TR) = 2000 ms, echo time (TE) = 35 ms, flip angle (FA) = 80°, field of view (FOV) = 211 mm, slice thickness = 3.0 mm, interslice distance = 0.3 mm, 135 dynamics, and 64 x 64 grid (Amsterdam protocol), or 64 x 60 grid (Groningen protocol), voxel size = 3.3 x 3.3 x 3.3 mm. Two spin echo EPI scans with opposing polarities of the phase-encode blips were acquired (TR =6000 ms, TE = 60 ms, all other parameters remained the same) which would later be applied to correct for distortions in the functional images caused by the susceptibility distribution of the subject's head (Andersson & Sotiropoulos, 2016; Smith et al., 2004). Additionally, high resolution, whole-brain T1-weighted sagittal brain images were acquired at the beginning of the scan protocol (TR = 400 ms, TE = min full, FA = 111°, FOV = 250 mm, slice thickness = 3.0 mm, interslice distance = 0.3 mm, and 256 x 192 grid, voxel size = 1 x 1 x 1 mm).

4.2.5 IMAGE ANALYSES

FIRST LEVEL ANALYSIS

For each subject, data were preprocessed using FLS feat (FMRI Expert Analysis Tool; FMRIB Analysis group, Oxford, UK; available from the FMRIB Software Library at_www.fmrib.ox.ac.uk/fsl). The first steps were performed separately for all the four experimental blocks. Blocks were only included if (1) there was at least one correct response for each of the four conditions (working memory and control conditions, high and low memory load), and (2) the block was complete, i.e., the scan was not aborted before the end of the block. In total, 91.3% of the blocks was included in the analyses. Functional images were corrected for head motion using rigid body transformations (MCFLIRT, FSL; Jenkinson, Bannister, Brady, & Smith, 2002), followed by a correction for the susceptibility distribution of the subject's head (TOPUP tool in FSL; Andersson & Sotiropoulos, 2016; Smith et al., 2004). To remove non-brain tissue from the functional scans and the T1-weighted structural images, the Brain Extraction Tool (BET; Smith, 2002) was applied. Subsequently, spatial smoothing was applied to the functional data using a 5-mm Full Width Half Maximum (FWHM) Gaussian Kernel. Smoothing was applied to improve signal-to-noise ratio by replacing the value of a single voxel by a weighted average of neighboring voxels. Finally, the experimental blocks were combined into a single 4D dataset per subject, which could be used for further analyses.

In order to remove artifacts from the subject's data, an independent-component analysis (ICA) was conducted using Multivariate Exploratory Linear Optimized Decomposition into Independent Components (MELODIC; Beckmann & Smith, 2005) for each subject's 4D dataset. MELODIC is a method by which a 4D dataset can be decomposed into spatial and temporal components. This way, activation and artefactual components can be distinguished, as they have unique spatial patterns (Kelly et al., 2010; Thomas, Harshman, & Menon, 2002). By using ICA, the data were represented by a multiplication of two matrices (see Box 1):

$$Y = T * M; \qquad (1)$$

in which Y represents the time course spatial maps (dimension time by voxel), T represents the component time course (dimension time by component) and M the component spatial maps (component by voxel). Based on the recommendation to use about one-fourth to one-fifth of the total of time points in the scans (Greicius, Srivastava, Reiss, & Menon, 2004), and previously widely adopted settings of 20-30 components for ICA (Smith et al., 2009), a fixed number of 30 components was extracted per subject. The spatial component maps were visually inspected for artefacts, and components representing artefacts were removed. The remaining components (T', M') were used to generate contrast images (i.e. a representation of differences in brain activation between different task conditions), using the following procedure:

1) A model representing the expected BOLD response was created for each of the task-conditions (X: dimension time by condition) using Statistical Parameter Mapping 12.0 (SPM 12.0 v6470, running in MATLAB 2017b). The task-conditions are presented in Table 4.1. Only correct trials were included to minimize variability in brain activation between different conditions, because differences in brain activation were expected during incorrect and omission trials as compared to correct trials. The model was created by convolving a stick function with a canonical Hemodynamic Response Function (HRF). Additionally, a constant was added to this model to capture an offset.

TABLE 4.1. Overview of all task-conditions in the visuospatial working memory task. Conditions used for this study (only correct trials) are shown in italics.

	Working memory trials		**Control trials**	
	Low load	High load	Low load	High load
Correct response	*Con1*	*Con4*	*Con7*	*Con10*
Incorrect response	Con2	Con5	Con8	Con11
Omission error	Con3	Con6	Con9	Con12

Note. Con = condition.

2) The time course of each of the remaining components T', was regressed against the model created in step 1 using Ordinary Least Square (OLS), resulting in an effect size per condition (B: dimension condition by component):

$$T' = X * B \qquad (2)$$

3) Two contrast vectors (c_1, c_2) were defined in order to reconstruct a contrast effect size map per subject (CM: dimension contrast effect size by voxel), representing differences in brain activation when comparing different conditions:

- A working memory contrast (c_1): successful working memory trials (Con1 and Con4) versus successful control trials (Con7 and Con10);
- A load difference contrast (c_2): successful high working memory load trials (Con4) versus successful low working memory load trials (Con1).

For each voxel in CM, the contrast effect size was reconstructed by summing the contrast effect size per component (c*B) across components, weighted by the corresponding value in M'. This way, components with larger effect sizes had a higher weight in reconstruction of the maps:

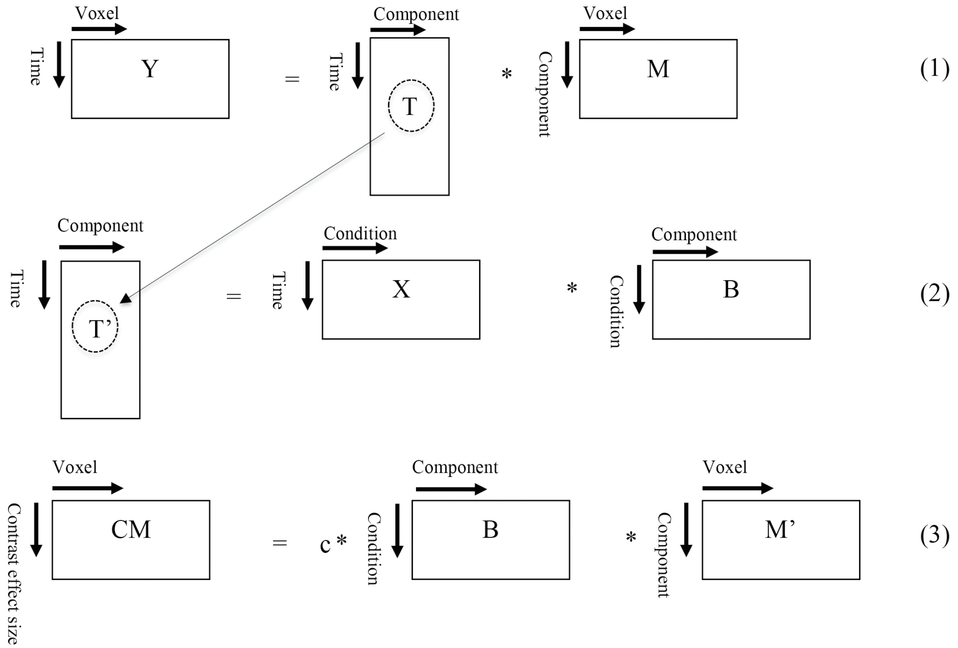
$$CM=c*B*M \qquad (3)$$

This resulted in a contrast image representing the activation differences between the conditions for each voxel per subject. A difference between the two sites was found in the scaling of the contrast-images, as the intensity scale of the images acquired in Groningen was five times larger than that of those acquired in Amsterdam. The images were therefore rescaled by dividing their intensity scale by its respective standard deviation.

4) The contrast image CM was coregistered to the subject's own 3D anatomical space and normalized to standard space by registration to an MNI-152 template. Normalization was used in order to match anatomical brain locations across subjects. This allows averaging brain activation patterns across subjects, which can therefore be used for further second level (group) analysis. The contrast CM images were spatially smoothed with an 8-mm FWHM Gaussian Kernel. The smoothing, co-registration and normalization steps were performed in SPM.

Children were excluded from the analysis if (1) more than 15 components were manually removed from the data (*n* = 3); (2) normalization had failed (n = 7), or (3) children were absent on testing days at school, and therefore had no score for working memory, cardiovascular fitness, or motor skills (*n* = 1). The final sample consisted of 80 children (87.0% of the total number of children that was scanned; 41 girls [51.3%]; 38 grade 3 children [47.5%]). An overview of the number of children that participated (separated by school, grade, and gender), and the final number of children that was included for the data analyses is presented in Appendix 5.

Box 1. Independent Component Analysis (ICA) and reconstruction of the contrast effect size maps



Y: 4D dataset time course spatial maps for a subject represented by the component time course (T) and the component spatial maps (M).

T': the component time course of the remaining components (after removing components with artefacts), represented by the condition time course (X) and the effect size per condition for each of the remaining components (B).

CM: contrast effect size map per contrast, represented by sum of the contrast effect size per component (c * B) and the component spatial maps for the remaining components (M').

c: contrast vector, either for the working memory contrast or for the load difference contrast:

c_1 = working memory contrast: successful working memory trials (Con1 and Con4) versus successful control trials (Con7 and Con10)

c_2 = load difference contrast: successful high working memory load trials (Con4) versus successful low working memory load trials (Con1)

4.2.6 ANALYSES

BEHAVIORAL DATA

A principal component analysis on the standardized scores of the gross motor skill tests was performed to calculate a Bartlett factor score. This analysis was performed on the total sample of 891 children in the '*Learning by Moving*' project (see van der Fels et al., subm.). The four gross motor skill components loaded highly onto one factor (> 0.6) and explained 48.2% of the total variance. This factor was used in the analysis as a measure of gross motor skills.

IBM SPSS Statistics version 25 was used to calculate Pearson correlations between the physical task scores (gross motor skills and cardiovascular fitness) and behavioral VSWM task scores (low working memory load trials, high working memory load trials, and low and high working memory trials together) . Level of significance was set at $p < 0.05$.

SECOND LEVEL FMRI ANALYSIS

SPM12 (v6470, running in Matlab 2017b) was used to analyze the fMRI data. In a first step, two General Linear Models (GLM) were created (one for each contrast) to capture the overall response. The contrast images (CM in box 1) from the first level analysis were added as dependent variable in the models. Additionally, scan site (Amsterdam or Groningen), gender, age and SES were included in the model as covariates of no interest. In a second step, a GLM was created for both contrasts with the factor score for gross motor skills as covariate of interest. Finally, a GLM was created for both contrasts with cardiovascular fitness as covariate of interest. If the covariates of no interest included in step 1 were significant, they were included in the models created in step 2 and 3 as well. Figures shown in this Chapter represent activation maps thresholded at significance level of $p < 0.01$ (uncorrected). The table and the text will represent results that survived the cluster level significance of $p < 0.05$, family wise error (FWE) corrected, initial threshold $p < 0.001$.

4.3 RESULTS

4.3.1 BEHAVIORAL RESULTS

Demographics and scores on cardiovascular fitness, gross motor skills and VSWM are shown in Table 4.2. Pearson correlations showed that gross motor skills were positively related to low working memory load trials, $r = .36$, $p = .001$, to high working memory load trials, $r = .24$, $p = .04$, and to all working memory trials, $r = .32$, $p = .004$. Cardiovascular fitness was positively related to low working memory load trials, $r = .28$, $p = .01$, to high working memory load trials, $r = .22$, $p = .05$, and to all working memory trials, $r = .27$, $p = .02$.

*TABLE 4.2***.** *Pearson correlations between the study variables, and descriptive statistics and test scores (means and standard deviations) of the total sample (n = 80).*

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Age (years)[a]	1								
2. Gender (% girls)	-.05	1							
3. SES[a]	-.08	.02	1						
4. Grade (% grade 3)	.80**	.07	.06	1					
5. Low VSWM load trials (% correct)[a]	.05	-.06	.21	.16	1				
6. High VSWM load trials (% correct)[a]	-.04	.03	.22*	.09	.75**	1			
7. All VSWM trials (% correct)[a]	.01	-.02	.23*	.14	.94**	.93**	1		
8. Gross motor skills (factor score)[a]	.27*	-.06	.02	.31**	.36**	.24**	.32**	1	
9. Cardiovascular fitness (stages)[a]	.20	-.26*	.15	.14	.28**	.22**	.27**	.49**	1
Mean (*SD*) or percentage	9.2 (.6)	51.3	4.6 (1.1)	47.5	70.7 (16.0)	66.0 (15.5)	68.4 (14.7)	.2 (1.0)	4.7 (1.9)

[1] Mean (*SD*); * $p < 0.05$; ** $p < 0.01$.

Note. Performance on low and high working memory significantly differed as measured with a paired sample t-test, t (80) = 4.245, $p < 0.001$; SES = socioeconomic status, obtained by a parental questionnaire. Level of parental education of both parents was requested and varied from 0 (no education) to 7 (postdoctoral education; Schaart, Mies, & Westerman, 2008). Average education level of both parents was used as a measure of SES. If the level of parental education was specified for only one of the parents, this level was used as a measure of SES for the child.

4.3.2 FMRI RESULTS

WORKING MEMORY CONTRAST

Brain activation during working memory trials compared to control trials, while controlling for the covariates of no interest that were included in step 1 (i.e. scan site, gender, age, and SES) are shown in Figure 4.3. Table 4.3 shows MNI coordinates of the significant clusters of brain activation. Significant clusters were located right in the angular gyrus and bilateral in the superior parietal cortex, the inferior temporal gyrus and the middle temporal gyrus ($p < .05$), indicating task related increases in activation in the angular and superior parietal areas, and task related decreases in the inferior and middle temporal areas. Results on the covariates (site, age, gender and SES) are presented in Appendix 6.

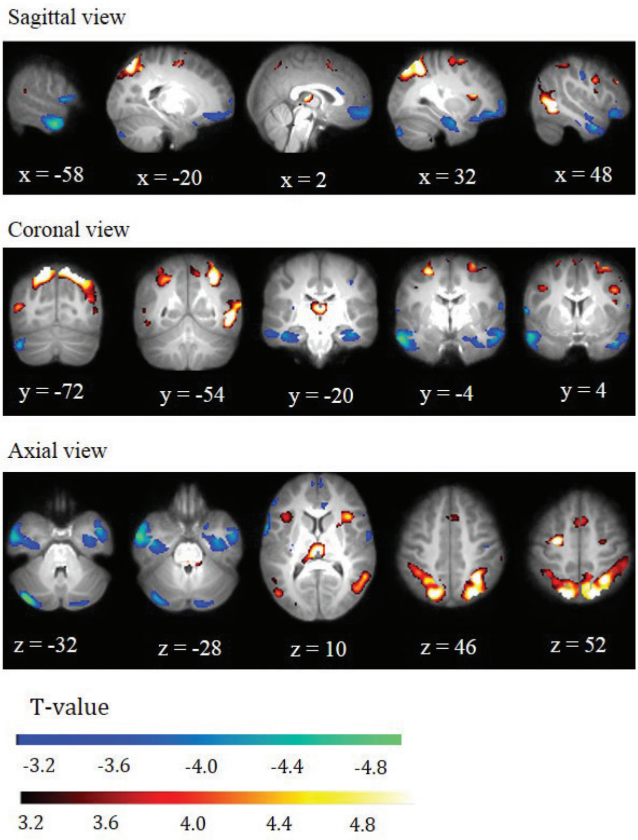


FIGURE 4.3. Brain activation for the working memory contrast. Axial (upper), coronal (middle) and sagittal (lower) view. Warm colours indicate activation in working memory trials as compared to control trials. Cool colours indicate deactivation in working memory trials as compared to control trials. MNI coordinates (x, y, and z) represent the location of the maximum intensity voxel.

TABLE 4.3. Significant clusters of brain activation associated with working memory, controlling for scan site, age, gender and SES.

				MNI coordinates[a]		
Cluster	Anatomical label(s)	Hemisphere	N voxels	X	Y	Z
1	Angular gyrus, superior parietal gyrus[b]	Right	3900	32	-54	46
2	Superior parietal gyrus[b]	Left	1562	-20	-72	52
3	Thalamus[a]	Bilateral	503	2	-20	10
4	Inferior temporal gyrus, middle temporal gyrus[c]	Left	6940	-58	-4	-28
5	Inferior temporal gyrus, middle temporal gyrus[c]	Right	1498	48	4	-32

Note: Activation for the working memory contrast that survived the cluster level significance of $p < .05$, family wise error (FWE) corrected, initial threshold $p < .001$. N voxels: number of voxels involved in the significant cluster (total brain volume consisted of 153138 voxels). [a.] Brain coordinates defined by the Montreal Neurological Institute (MNI), based on which the location of (de)activated clusters of voxels can be identified. MNI coordinates represent the location of the maximum intensity voxel. [b.] Brain areas indicating activation in working memory trials as compared to control trials. [c.] Brain areas indicating deactivation in working memory trials as compared to control trials.

LOAD DIFFERENCE CONTRAST

Although the percentage of correct trials was higher for low working memory load than for high working memory load, analysis on the load difference contrast revealed no significant differences in activation between low and high working memory load trials (all $p > .05$). Therefore, this contrast was not further examined.

GROSS MOTOR SKILLS AND CARDIOVASCULAR FITNESS

The results regarding gross motor skills and cardiovascular fitness revealed no significant associations between either gross motor skills or cardiovascular fitness with brain activation ($p > .05$), indicating that both gross motor skills and cardiovascular fitness were not related to VSWM-related brain activation.

4.4 DISCUSSION

This study examined VSWM-related brain activation in children, and how this was associated with either cardiovascular fitness and/or motor skills. VSWM-related brain activation was found in the angular gyrus (right hemisphere), the superior parietal cortex (bilateral), and the thalamus (bilateral); and VSWM-related deactivation was found in the inferior and middle temporal gyri (bilateral). There were no differences in activation between low and high working memory load trials. Gross motor skills and cardiovascular fitness were not associated with VSWM-related brain activation, while there were significant relations between behavioral VSWM performance during scanning and both gross motor skills and cardiovascular fitness.

4.4.1 VSWM-RELATED BRAIN ACTIVATION PATTERNS

The brain regions that were found to be involved in VSWM task performance are partly in accordance with brain regions found to be associated with VSWM in the literature. As summarized in a meta-analysis by Wager & Smith (2003), spatial storage tasks (such as the VSWM task) most frequently activate the superior parietal cortex, which was also found in our study. Furthermore, it has been shown that the prefrontal cortex is interconnected with posterior parietal and temporal cortices, and with subcortical areas (such as the thalamus) during visuospatial working memory tasks (Selemon & Goldman-Rakic, 1988). We could only partly confirm these VSWM-related neural circuitries. Our results showed deactivation in prefrontal areas associated with VSWM, but this deactivation did not survive the significance threshold (Figure 4.2). Additionally, we found deactivation in the inferior and middle temporal gyrus. It is difficult to explain this deactivation in temporal areas, as previous studies have constantly found increased activation in working memory trials as compared to control trials, based on which it is expected that more brain activation is required during working memory trials as compared to control trials. From our study, the neural circuitry supporting VSWM seem to involve parietal (activation) and temporal cortical regions (deactivation) and the thalamus (subcortical region; activation).

There were no differences in brain activation between the high working memory load trials and the low working memory load trials. This was unexpected based on a previous study by van Ewijk and colleagues (2015) in which the same task was used. In their study, differences in brain activation were found in the frontal, temporal, occipital and parietal regions in 8-30 years old participants when comparing trials of different loads. Possibly, the accuracy of task performance can explain this unexpected finding, as the children in our study performed worse on both low and high working memory load trials than the participants in the study by van Ewijk and colleagues (2015). Therefore, the difference in working memory load related activation patterns might be caused by the fact that children in our study had difficulties with both the high and low working memory trials, leading to a lack of differences in brain activation between those trials. That our children performed worse on both trials possibly had to do with the fact that the age range of our children was much smaller, with ages between 8-10 years, compared to 8-30 year old participants in the study by van Ewijk and colleagues (2015).

4.4.2 RELATIONS WITH GROSS MOTOR SKILLS AND CARDIOVASCULAR FITNESS

Neither gross motor skills nor cardiovascular fitness was related to the neural circuitry supporting VSWM. Although both gross motor skills and cardiovascular fitness were significantly related to behavioral VSWM performance during scanning, we could not confirm the hypothesis that the neural circuitry supporting VSWM underlie the relations of gross motor skills and cardiovascular fitness with VSWM. Our results are contradictory to the studies by Chaddock and colleagues (2012) and Voss and colleagues (2011), where associations between cardiovascular fitness and brain activation were found, although it should be noted that brain activation was measured during an inhibition task in these studies. The study by Chaddock et al. (2012) showed changes in brain activation over experimental blocks, which differed between high and low fit children. It was argued that children with higher cardiovascular fitness were better able to remain accurate over the four blocks than children with lower cardiovascular fitness were, because of differences in underlying changes in brain activation over the four blocks. For future research it seems interesting to investigate brain activation changes across experimental blocks for VSWM tasks as well, and to relate those changes to cardiovascular fitness. Although it is not clear whether the same argumentation holds for gross motor skills, as no other studies have yet investigated relations between gross motor skills and VSWM-related brain activation, it would be interesting for future studies to start exploring how brain activation changes during a VSWM task relate to gross motor skills as well.

4.4.3 STRENGTHS, LIMITATIONS, AND FUTURE DIRECTIONS

Strengths of this study include the large sample of typically developed children that was examined. This enabled us to get a detailed and reliable insight in brain activation during a VSWM task. Additionally, by including both cardiovascular fitness and gross motor skills it was possible to examine underlying brain mechanisms in the relation between gross motor skills and cardiovascular fitness and VSWM performance.

However, this study also showed that it is difficult to perform a (f)MRI study in young children, as participating children had difficulties with laying still throughout the scanning protocol. The protocol also included a DTI and resting state scan, which resulted in a total scan time of approximately one hour. The active state scan used for this study was the last part of the protocol, which provides an explanation for why it was so difficult for children to remain still, resulting in high movement parameters in the fMRI data. We therefore had to apply extensive preprocessing steps to remove movement artefacts and to clean the data to minimize the effects of the movement.

By keeping the working memory load low (only three or five circles per trial), we tried to bring about ceiling effects in task performance. Ceiling effects minimize inter-individual differences in behavior during scanning, thereby making it easier to interpret differences in brain activation (Klingberg et al., 2002). Despite this effort, no ceiling effects in task performance were found, neither for low working memory load trials, nor for high working memory load trials. We tried to minimize this problem by only taking into account trials with correct responses. It is recommended for future studies to investigate brain activation during incorrect trials as well.

The mechanisms that we used to explain the relations of gross motor skills and cardiovascular fitness with VSWM refer to the effects of physical activity interventions on cognition. According to these mechanisms, physical activity interventions result in improved cognition via either improvements in cardiovascular fitness, or involvement of brain areas also important for cognitive task performance during gross motor skill training. As we only examined cross-sectional relations in this study, it is of interest for future research to examine the effects of physical activity interventions on VSWM-related brain activity as well, to see whether these mechanisms hold.

4.4.4 CONCLUSION

In conclusion, regions in the parietal and temporal cortices and the thalamus were found to be important for VSWM performance in 8-10 year old children. Activation patterns did not differ between high and low working memory load trials. Although gross motor skills and cardiovascular fitness were related to VSWM performance, they were not related to VSWM-related brain activation. Based on these results, we could not confirm the hypothesis that brain activation patterns underlie the relation between gross motor skills and/or cardiovascular fitness and VSWM performance. It is recommended for future studies to start exploring brain activation changes during a VSWM task, and how these changes relate to gross motor skills and cardiovascular fitness. Additionally, future studies should investigate whether physical activity interventions that lead to changes in cardiovascular fitness and gross motor skills, also bring about changes in VSWM related brain activity.


5

EFFECTS OF AN AEROBIC AND A COGNITIVELY-ENGAGING PHYSICAL ACTIVITY INTERVENTION ON ACADEMIC ACHIEVEMENT: A CLUSTER RCT

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ABSTRACT

This cluster randomized controlled trial compares the effects of two school-based physical activity interventions (aerobic vs. cognitively-engaging) on reading, mathematics, and spelling achievement; and whether these results are influenced by volume of moderate-to-vigorous physical activity, and initial academic achievement. Twenty-two primary schools participated, where a third and fourth grade were randomly assigned to the intervention or control group. Intervention groups were randomly assigned to a 14-week aerobic or cognitively-engaging intervention, receiving four lessons a week. Control groups followed their regular physical education program. Academic achievement of 891 children (mean age 9.17 years, 49.4% boys) was assessed before and after the interventions using standardized tests. Posttest academic achievement did not significantly differ between the intervention groups and the control group. A higher volume of moderate-to-vigorous physical activity resulted in better posttest mathematics achievement in both intervention groups, and posttest spelling achievement in the cognitively-engaging intervention group specifically. Compared to the control group, lower achievers in reading performed better in reading after the cognitively-engaging intervention. A combination of moderate-to-vigorous physical activity and cognitively-engaging exercises is argued to have the most beneficial effects. Future interventions should take into account quantitative and qualitative aspects of physical activity, and children's initial academic achievement.

5.1 INTRODUCTION

The positive effects of physical activity on children's health, physical fitness, and motor development are well known (Morgan et al., 2013; Wu et al., 2017). Following these results, it is unfortunate that children often get only few opportunities to be physically active during the school day, mainly because many educators believe that spending time on physical activity interferes with the main aim of education, namely improving academic achievement (Howie & Pate, 2012). Contrary to what is often believed, there is little evidence for the adverse effects of physical activity on academic performance (Singh et al., 2019), with some studies rather suggesting that physical activity can have beneficial effects on academic performance (de Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018a).

5.1.1 SCHOOL-BASED PHYSICAL ACTIVITY PROGRAMS

Results on physical activity programs implemented in the school-setting are inconsistent, however, with some studies reporting positive effects of school-based physical activity on academic achievement (Ericsson, & Karlsson, 2014), whereas others find mixed (Resaland et al., 2016), or null effects (Coe, Pivarnik, Womack, Reeves, & Malina, 2006). These inconsistent findings might be due to the wide variation in the type and intensity of the physical activities implemented in different studies (Donnelly et al., 2016). Most studies examining effects of school-based physical activity programs have focused on quantitative aspects (i.e. duration, frequency, and intensity), providing evidence for the effectiveness of aerobic physical activity at a moderate to vigorous intensity level (MVPA; Coe et al., 2006; Mura, Vellante, Nardi, Machado, & Carta, 2015), and indications of dose-response effects (Davis et al., 2011; Mura et al., 2015). Studies mostly focus on cognitive outcomes, reporting the strongest effects of MVPA for executive functioning (EF; Álvarez-Bueno et al., 2017), the cognitive functions that guide and control goal-directed behavior (Diamond, 2012). The positive effects on EF are thought to be brought about via changes in the brain, such as an upregulation of growth factors and monoamines, increased cerebral blood flow, neurogenesis, and improved brain activation, mainly in brain areas also involved in EF (Lubans et al., 2016). As EFs are closely related to academic achievement (Diamond, 2012), it has been suggested that physical activity's effects on academic achievement are a result of improved EFs (Donnelly et al., 2016). Therefore, characteristics of physical activity that are beneficial for EF, such as intensity and dose, can be expected to also aid academic performance, although more research is needed to substantiate this claim.

More recent research has focused on qualitative aspects (i.e. type) of physical activity (Crova et al., 2014; Pesce, 2012). Although this line of research has not yet examined effects of different types of physical activity on academic achievement, some first evidence indicates that EFs benefit more from cognitively-engaging physical activity, compared to 'simple' repetitive activities involved in aerobic physical activity (Crova et al., 2014; Pesce, 2012). Cognitive engagement is defined as "the degree to which the allocation of attentional resources and cognitive effort is needed to master difficult skills" (Tomporowski, McCullick, Pendleton, & Pesce, 2015). This type of physical activity is for example seen in team sports, where children have to focus their attention, plan a strategy, collaborate with teammates, and so on. It is argued that cognitively-engaging physical activity requiring complex, controlled and adaptive cognition, activates brain areas that are also involved in higher-order cognition, thereby aiding cognitive development (Álvarez-Bueno et al., 2017; Lubans et al., 2016). Considering the close link between EF and academic achievement (Diamond & Lee, 2011; Howie & Pate, 2012; Lubans et al., 2016), it can be hypothesized that this type of physical activity will be beneficial for academic achievement as well. Research focusing on academic outcomes is needed to confirm this hypothesis.

The mixed results on the effectiveness of school-based physical activity interventions can also be attributed to the fact that not all children benefit to the same extent. Several studies suggest that physical activity has the most beneficial effects on cognition (Diamond & Lee, 2011; Drolette et al., 2014; Sibley & Beilock, 2007) and academic achievement (Resaland et al., 2016) for children with the poorest performance at baseline, possibly because they have most room for improvement. These children are a vulnerable population, being at risk of school dropout due to their cognitive difficulties (Rumberger & Lim, 2008), making it of great importance to examine whether physical activity can provide an effective means for improving their academic performance.

5.1.2 THE PRESENT STUDY

As it remains yet unknown whether the effectiveness of physical activity interventions on academic achievement depends on the type of activities involved, the present study examines the causal effects of two school-based physical activity interventions, an aerobic physical activity intervention focusing on MVPA, and a cognitively-engaging physical activity intervention, on primary school children's achievement in reading, mathematics, and spelling. Second, to get a better understanding of characteristics that influence intervention effectiveness, it is examined whether the amount of MVPA is related to intervention effectiveness, because previous studies have provided evidence for MVPA (Coe et al., 2006; Mura et al., 2015) and dose-response effects (Davis et al., 2011; Mura et al., 2015). Third, it is examined whether children's prior level of achievement is related to the intervention effects, with the expectation of larger effects for lower-achieving children at baseline.

5.2 METHODS

5.2.1 DESIGN

A cluster power analysis with .40 as effect size (Davis et al., 2011; Sibley & Etnier, 2003) resulted in a required sample of ≥ 40 classes (20 schools), with 25 children per class (power .90, intraclass correlation $\rho = .10$, 1-tailed, $a = .05$).

To be eligible, schools had to be regular primary schools, and only third and fourth grade classes could participate. At each school, a third and fourth grade class participated. Twenty-four schools were recruited in the school year 2015/2016 and were matched into pairs based on school size. For one of the paired schools it was randomly determined which intervention (aerobic or cognitively-engaging) would be implemented, and which grade would serve as intervention group. The same intervention was assigned to the second school in the pair, but the other grade class would receive the intervention. Randomization was performed by an independent researcher using numbered containers. Intervention assignment was only blinded for research assistants, not for teachers and children, as the interventions implicated changes in the physical education schedule. Two schools withdrew from participation after randomization, but before the start of the pretest. Eleven schools received the aerobic intervention and eleven schools the cognitively-engaging intervention. Figure 7.1 in Appendix 7 shows the number of classes and children at each stage of the study.

5.2.2 PARTICIPANTS

In total, 891 children of 22 primary schools participated. Characteristics of participating children are presented in Table 5.1. Written informed consent was acquired for all children from their legal guardians. The study was approved by the ethical board of the Vrije Universiteit Amsterdam, the Netherlands and registered in the Netherlands Trial Register (number NTR5341).

TABLE 5.1. Baseline characteristics of children, for the total sample and separately for the control group, aerobic intervention group and cognitively-engaging intervention group.

	Total sample (*n* = 891)	Control group (*n* = 430)	Aerobic intervention group (*n* = 221)	Cognitively-engaging intervention group (*n* = 240)
Grade, *n* grade 3 (%)	456 (51.2)	235 (54.7)[a]	98 (40.0)[a]	123 (56.9)[a]
Gender, *n* boys (%)	440 (49.4)	219 (51.0)	114 (46.5)	107 (49.5)
Age, in years (SD)	9.2 (.7)	9.2 (.67)[b]	9.3 (.6)[b]	9.06 (.6)[b]
SES[c] (SD)	4.5 (1.0)	4.5 (1.0)	4.4 (.9)	4.61 (1.1)

[a.] Compared to what could be expected based on chance, there was a higher percentage of third grade children in the control group, and a higher percentage of fourth grade children in the aerobic intervention group.

[b.] Controlling for grade level, children in the aerobic intervention group were significantly older than children in the control group (p = .02), and the cognitively-engaging intervention group (*p* < .001); and children in the cognitively-engaging intervention group were significantly younger than children in the control group (*p* < .001). [c.] SES = socioeconomic status; mean parental education level of both parents, measured via a parent questionnaire, ranging from no education (0) to postdoctoral education (7; Schaart, Mies, & Westerman, 2008). In case only one of the parents' educational levels was specified, this was used as a measure of the child's SES.

5.2.3 INTERVENTIONS

Two fourteen-week interventions were designed by researchers (experts in Human Movement Sciences) and Physical Education teachers: an aerobic intervention and cognitively-engaging intervention, each consisting of four lessons per week, thereby doubling the number of physical education lessons children received. The 14 week intervention period was chosen for feasibility reasons (this precisely fitted within a primary school year semester), and because previous studies using similar intervention periods have resulted in positive effects as well (de Greeff et al., 2018a). All intervention lessons had a predetermined duration of 30 minutes. The focus of the aerobic intervention was on MVPA, aiming to elicit high heart rate levels to promote children's aerobic fitness. Playful forms of aerobic exercise were included that were highly repetitive and automated, for example relays, running or individual exercises such as doing squats. The cognitively-engaging intervention focused on challenging cognition and motor skills via games (e.g. dodgeball and soccer) and exercises (e.g. balancing, throwing, and catching) that required complex coordination of movements, and that included complex and fast-changing rules to engage children's cognitive skills (Best, 2010). The interventions were delivered by external physical education teachers, hired for the project, during regular and extra physical education lessons for 14 weeks in the school year 2016/2017. Teachers were instructed on how to implement the interventions during a training session of three hours, led by the intervention developers, during which they were familiarized with the goals and the content of the interventions. In addition, they were provided with a manual including a detailed description of each intervention lesson. Observations on intervention implementation were conducted at least two times in each class, after which feedback was provided to the intervention teacher. Control groups followed their regular physical education lessons twice a week.

During two lessons (one in the first week and one in the last week of the intervention, chosen based on representativeness of the lesson for the intervention), intensity of the lessons was monitored in all three groups. All children wore an accelerometer (ActiGraph GT3x+, Pensacola, FL, USA) on their right hip to measure the intensity with which they participated. Mean time in MVPA (in minutes) over the two lessons was calculated (see Appendix 8). For the intervention groups, volume of MVPA was calculated by multiplying the mean time in MVPA over the two lessons by the number of intervention lessons followed. This was not done for children the control group, as no information was available on the number of lessons that they followed.

5.2.4 MATERIALS

Before and after the interventions, all children were tested on academic achievement during the school hours at their own school. The tests that were used are part of a standardized test battery used by most primary schools in the Netherlands, which has been tested on reliability and validity in a large sample of Dutch primary school students (Tomesesen, Weekers, Hilte, Jolink, & Engelen, 2016a; Hop, Janssen, & Engelen, 2016; Tomesen, Wouda, & Horsels, 2016b). Tests were grade-appropriate, with third grade children making an easier version of the tests than fourth grade children did. All tests were conducted following standardized protocols. Instructed research assistants administered the reading and mathematics tests. The children's teacher conducted the spelling test (a dictation), as children were already familiarized with their teacher's voice and pronunciation. For all tests, the number of correctly answered questions was used as score of academic ability.

In the reading comprehension test, children read several types of texts (e.g. narrative or informative) and answered 25 multiple choice questions about those texts. Reliability (test-retest reliability = .90) and validity of the reading test are good (Tomesen et al., 2016a). The mathematics test consists of 20 questions measuring general mathematics ability. Assignments include basic arithmetic operations and mathematical problems that have to be extracted from text. Reliability (test-retest reliability > .90) and validity of the mathematics test are good (Hop et al., 2016). The spelling test consists of a dictation in which the teacher reads out a sentence and repeats one word out of that sentence (25 words in total), which children have to correctly write down. Reliability (test-retest reliability > .90) and validity of the spelling test are good (Tomesen et al., 2016b). The tests were administered in a fixed order, on three different days, within a time frame of two weeks.

5.2.5 ANALYSES

Baseline differences between the three groups were examined using χ^2-analyses (grade and gender) or Analysis of Variance (ANOVA; age, SES, and academic achievement) and follow-up analyses with Bonferroni-correction in IBM SPSS Statistics 25.0. Subsequently, multilevel path models using maximum likelihood estimation with robust standard errors (MLR) were built in Mplus 7.31 (Muthén & Muthén, 1998-2006) to examine the intervention effects. Intervention effects were examined by relating two dummy variables, contrasting the aerobic intervention to the control condition (1), and the cognitively-engaging intervention to the control condition (2), to posttest scores in reading, mathematics, and spelling. The covariates pretest score, SES, age, gender, and grade were related to academic achievement pretest and posttest scores. Covariances were added between scores in reading, mathematics, and spelling, both at pretest and at posttest. Further, covariances between age and SES and between age and grade were entered because of significant relations between these covariates.

For the two intervention groups, volume of MVPA was added as predictor of posttest academic achievement scores in a second model. Gender and condition were related to MVPA in this model, as differences between boys and girls, and between intervention groups were expected. An interaction term between group and volume of MVPA was added in a follow-up analysis, to examine whether this relation differed for the two intervention conditions.

Lastly, a third model was analyzed with an interaction between pretest scores and the dummy variables for condition to examine whether children's initial achievement level was related to the intervention effects. To improve model fit, scores were mean centered, and covariances between the interaction terms and corresponding pretest scores, and between spelling posttest and reading pretest were added.

The root mean square error of approximation (RMSEA), comparative fit index (CFI), and standardized root mean square residual (SRMR) were used to evaluate model fit, with cut-offs of .06, .90, and .08 respectively (Hu & Bentler, 1999). Standardized estimates of path coefficients (βs) and corresponding *p*-values were obtained for significance testing. For the models examining the relations with MVPA and initial performance, only significant relations ($p < .05$) are reported, with further results in Appendix 9.

5.3 RESULTS

5.3.1 BASELINE CHARACTERISTICS

There was an unequal distribution of conditions over grades (χ^2 (2) = 6.21, $p = .045$; see Table 5.1) and, consequently, there were significant age differences between the groups (F (2, 888) = 10.96, $p < .001$; see Table 5.1). Children in the three groups did not significantly differ on socioeconomic status (SES) and gender. Table 5.2 presents mean pretest and posttest scores for reading, mathematics, and spelling for the three groups. Controlling for grade level, scores in reading, mathematics, and spelling did not significantly differ at pretest (F (6, 1650) = 1.34, $p = .23$).

TABLE 5.2. Average pretest and posttest scores (n correct) and standard deviations in reading, mathematics and spelling for the three conditions.

	n	Control group	*n*	Aerobic intervention group	*n*	Cognitively-engaging intervention group
Reading						
Pretest	401	18.2 (4.7)	212	18.8 (4.3)	239	17.9 (5.3)
Posttest	417	19.4 (4.7)	214	19.8 (4.3)	237	19.8 (4.5)
Mathematics						
Pretest	419	14.4 (4.2)	221	14.5 (4.4)	238	14.3 (4.5)
Posttest	414	15.8 (3.8)	214	15.6 (3.8)	237	15.8 (3.8)
Spelling						
Pretest	416	18.3 (5.3)	214	18.5 (4.9)	240	17.8 (5.7)
Posttest	413	20.3 (4.3)	215	20.4 (4.3)	236	19.6 (5.1)

5.3.2 INTERVENTION EFFECTS

The model examining the intervention effects on posttest scores in reading, mathematics, and spelling had a good fit to the data (χ^2 (21) = 48.00, RMSEA = .04, CFI = .99, SRMR = .05). The dummy variable contrasting the aerobic intervention group to the control group was not significantly related to posttest reading achievement (β = .02 (.03), *p* = .60, 95% CI [-.04 to .07]), mathematics achievement (β = -.02 (.03), *p* = .58, 95% CI [-.08 to .04]), or spelling achievement (β = .01 (.03), *p* = .77, 95% CI [-.05 to .07]). The dummy variable contrasting the cognitively-engaging intervention group to the control group was not significantly related to posttest reading achievement (β = .04 (.03), *p* = .19, 95% CI [-.03 to .09]), mathematics achievement (β = -.004 (.03), *p* = .88, 95% CI [-.08 to .04]), or spelling achievement (β = -.04 (.03), *p* = .13, 95% CI [-.10 to .01]).

5.3.3 MODERATE-TO-VIGOROUS PHYSICAL ACTIVITY

As second aim, volume of MVPA was related to the effectiveness of the interventions. Volume of MVPA significantly differed between the two intervention groups (*t* (406) = 9.95, *p* < .001, 95% CI [1.85 to 2.76]), with a significantly higher volume of MVPA in the aerobic intervention group (mean = 9.3 hours, *SD* = 2.5) than in the cognitively-engaging intervention group (mean = 7.0 hours, *SD* = 2.14). A relation between condition and MVPA was added to control for this difference.

A model with an added relation between volume of MVPA and academic achievement posttest scores resulted in an adequate fit (χ^2 (21) = 55.49, RMSEA = .06, CFI = .98, SRMR = .07). Volume of MVPA was positively related to posttest mathematics achievement (β = .09 (.04), *p* = .02, 95% CI [.02 to .17]), see Figure 5.1. This relation did not differ between the two groups (β = .07 (.13), *p* = .60, 95% CI [-.19 to .33]).

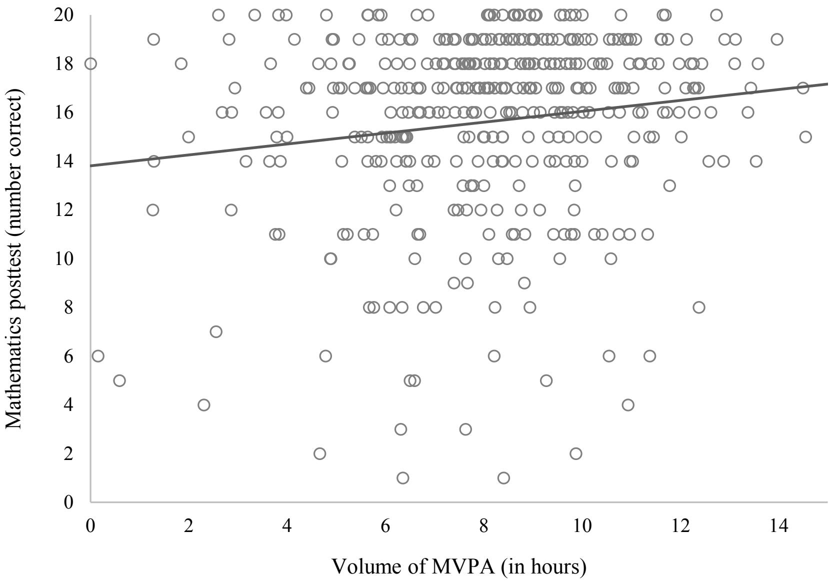

FIGURE 5.1. The relation between volume of MVPA and mathematics posttest scores for the two intervention groups.

A significant interaction between volume and group was found for spelling (β = .24 (.10), *p* = .012, 95% CI [.05 to .43]); volume of MVPA was positively related to posttest spelling achievement in the cognitively-engaging intervention group, but not in the aerobic intervention group, see Figure 5.2.

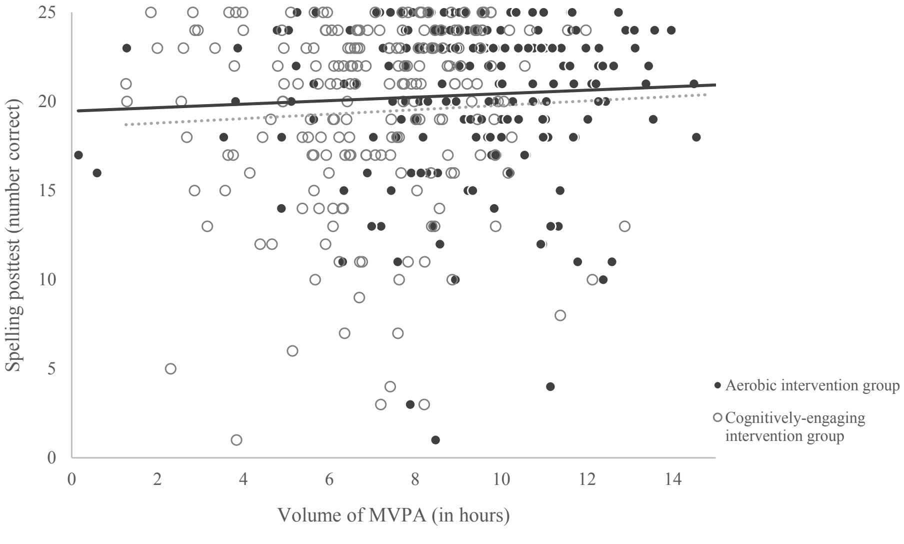

FIGURE 5.2. The relation between volume of MVPA and spelling posttest scores for the two intervention groups.

5.3.4 INITIAL ACHIEVEMENT

The third aim was to examine whether children's initial achievement level was related to the intervention effects. The model had an adequate fit to the data (χ^2 (62) = 236.72, RMSEA = .06, CFI = .95, SRMR = .09). Children with lower performance in reading at baseline performed better in reading at the posttest in the cognitively-engaging intervention group than in the control group (β = -.06 (.03), *p* = .03, 95% CI [-.11 to -.01]), see Figure 5.3.

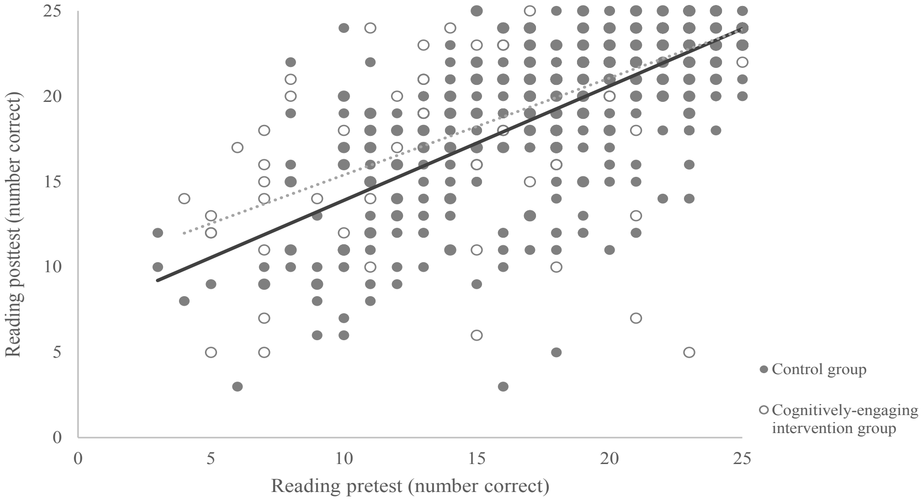

FIGURE 5.3. Relation between reading pretest and reading posttest for the control group and the cognitively-engaging intervention group.

5.4 DISCUSSION

This study is the first to directly compare the effects of two types of physical activity on children's academic achievement, one focused on aerobic and one on cognitively-engaging physical activity. The interventions did not have significant effects on primary school children's reading, mathematics, or spelling performance. Importantly, there were indications of dose-response effects, as children who were exposed to a higher volume of MVPA performed better in mathematics at the posttest in both intervention groups, and had better posttest spelling achievement in the cognitively-engaging intervention group specifically. Further, effects of the cognitively-engaging intervention depended on children's initial achievement level, with better posttest reading achievement for lower achievers in reading.

5.4.1 DOSE-RESPONSE EFFECTS

Corroborating previous results showing that the effectiveness of physical activity interventions on academic achievement remains yet inconclusive (Donnelly et al., 2016; Singh et al., 2019), we did not find overall effects of the physical activity interventions. A dose-response effect was found however, which is in line with earlier research (Davis et al., 2011; Mura et al., 2015), suggesting that independent of the *type* of activities involved, a high enough volume of MVPA is necessary to positively affect academic achievement, at least in mathematics. However, although this type of physical activity focusing solely on MVPA had positive effects on mathematics, we found positive effects on both mathematics and spelling for children who engaged in cognitively-engaging physical activity with a higher volume of MVPA. Although we did not directly examine the effects of an intervention combining MVPA with cognitive engagement, it seems that a combination of MVPA and cognitively-engaging physical activity has the most spread-out effects on academic achievement, suggesting that it is important to consider both quantitative and qualitative aspects of physical activity when aiming to improve academic achievement. This same conclusion was reached in a recent study, in which an intervention consisting of team games (targeting cognition and inducing MVPA) had stronger effects on cognition than a regular physical education program and a program focusing on physical exertion (Schmidt, Jäger, Egger, Roebers, & Conzelmann, 2015).

Following this conclusion, it is likely that there are different mechanisms that can explain the effects of physical activity on academic achievement simultaneously. These might be related to the neurobiological effects of physical activity: changes in brain structure and functioning as a result of aerobic physical activity, and the co-activation of brain areas needed for academic tasks during cognitively-engaging physical activity. Additional mechanisms might be at play at the same time, such as behavioral mechanisms (e.g. improved on task-behavior, better sleep patterns) or psychosocial mechanisms (e.g. improved self-esteem, increased school engagement) (Lubans et al., 2016). As the intervention programs in the present study focused on either MVPA or cognitive engagement, we are not able to formulate conclusions on the exact mechanisms that can explain the effects of physical activity on academic achievement. To get more insight into this, it would be interesting for future research to further examine whether physical activity that combines MVPA and cognitive engagement has the most beneficial effects on academic achievement. The results presented here strongly point in this direction.

5.4.2 SPECIFICITY OF INTERVENTION EFFECTIVENESS

The specific results for the different academic domains can possibly be explained by the underlying skills needed to perform well in the specific domains. Spelling performance mainly relies on automatized skills (Farrington-Flint, Stash, & Stiller, 2008). Automatization of skills can be considered an important factor for the intensity with which children participated in the cognitively-engaging intervention. That is: practicing complex skills such as those included in the cognitively-engaging intervention is difficult at a high intensity level due to the high cognitive load associated with complex skills (Sweller, Ayres, & Kalyuga, 2011). With enough training, these skills will become more automated however (Anderson, 1982; Fitts, 1964), reducing cognitive load, and making it possible to practice at a higher intensity. Children who were engaged in cognitively-engaging physical activity with a higher volume of MVPA will therefore have automated the complex skills to a larger extent, possibly being beneficial for their spelling performance. Mathematics relies on a combination of complex skills and automatization (Geary, 2004), suggesting that both a high enough intensity and cognitive engagement can result in improved academic performance. For future studies, it seems important to further examine these hypotheses by focusing on how physical activity affects achievement in the different academic domains.

As expected, the effects of the cognitively-engaging intervention differed depending on children's initial academic achievement, with better posttest performance for lower-achieving children in reading. Motor skills (the focus of the cognitively-engaging intervention in the present study) have already been related to reading comprehension (de Bruijn et al., 2019 [Chapter 3]). This relation was explained by the similarity of both skills, in that they are complex skills requiring controlled and effortful processing. Academic skills of lower-achieving children are more likely to benefit from this type of intervention, as they have most room for improvement (Diamond & Lee, 2011; Drolette et al., 2014; Resaland et al., 2016; Sibley & Beilock, 2007).

5.4.3 STRENGTHS, LIMITATIONS, AND DIRECTIONS FOR FUTURE RESEARCH

Strengths of this study include the large sample size, the design, and the use of standardized tests. An important limitation is that the interventions changed both the amount and the content of physical education lessons. Therefore, no definite conclusions can be drawn about whether it was the type or the amount of physical activity, or a combination, that caused the effects. For future studies, it is important to change one of the parameters at a time in order to disentangle the effects of type compared to amount of physical activity. Still, as the amount of physical activity was enhanced by using two different types of physical activity, it is possible to directly compare the effects of these two interventions. As a second limitation, MVPA was only recorded in two of the 56 lessons. Although these intervention lessons were chosen based on representativeness of the interventions, it can be questioned whether this measure adequately reflects the volume of MVPA during the interventions. Lastly, the amount of cognitive engagement during the interventions was not measured, making it difficult to validate the implementation of the cognitively-engaging intervention. Studying children's cognitive engagement is challenging in practice (Sinatra, Heddy, & Lombardi, 2015), which is why it was chosen not to include this measure in the present study. For future studies, it seems important to find reliable instruments and procedures to tackle this issue.

5.4.4 CONCLUSION

This study found no significant effects of two physical activity interventions on academic achievement, a conclusion that corroborates existing literature in which mixed findings on the effectiveness of physical activity are reported (Álvarez-Bueno et al., 2017; Donnelly et al., 2016; Singh et al., 2019). Most importantly, the results support previous conclusions that spending more time on physical activity during the school day does not go at the expense of academic achievement (Donnelly et al., 2016). Even better, it seems that physical activity can have beneficial effects on children's academic achievement, as long as the content of the activities involved is taking into account. Although not explicitly studied, the results presented here suggest that activities that combine a moderate-to-vigorous intensity level with cognitive engagement will have the most beneficial effects on academic achievement. This is an important hypothesis to elaborate upon in further research, as the effects of physical activity extend way beyond the academic domain, being important for amongst others children's physical fitness, motor skill development, and health and wellbeing (Kohl & Cook, 2013).

6

EFFECTS OF AN AEROBIC AND A COGNITIVELY-ENGAGING INTERVENTION ON BRAIN ACTIVATION DURING A VISUOSPATIAL WORKING MEMORY TASK*

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* This chapter has shared first authorship with I. M. J. van der Fels. Both authors have equally contributed to this chapter, order of authors is alphabetically.

ABSTRACT

The effects of physical activity on children's cognition and academic achievement are often explained by referring to changes in underlying brain activation. Different types of physical activity are thought to differently affect brain activation patterns. This study is the first to examine the effects of two 14-week physical activity interventions (an aerobic physical activity intervention and a cognitively-engaging physical activity intervention) on primary school children's brain activation during a visuospatial working memory task, using Functional Magnetic Resonance Imaging (fMRI). Data was collected from 92 children (51.1% girls, mean age of 9.14 years). Children were tested before and after the interventions consisting of four lessons per week, which focused either on physical activity at a moderate-to-vigorous intensity level (aerobic), or physical activity including complex rules and movements (cognitively-engaging). Children in the control group followed their regular physical education program of two lessons per week. Mass univariate analysis did not reveal differences between the three groups in pretest-posttest changes in brain activation patterns. However, exploratory pattern analyses revealed pretest-posttest changes in brain activation that differed between the three groups, mainly consisting of activation differences in frontal, occipital, and parietal cortices.

6.1 INTRODUCTION

The positive effects of physical activity on children's cognition and academic achievement are often explained by referring to changes in underlying brain activation patterns (Best, 2010; Donnelly et al., 2016). Supporting this hypothesis, several studies have shown that children's brain activation patterns change as a result of physical activity interventions. Interestingly, different types of physical activity are expected to result in different adaptations in the brain, because of different underlying mechanisms (Voelcker-Rehage & Niemann, 2013). Studies have not yet examined this assumption when looking at effects on children's brain activation however. Regarding the important role that changes in brain activation play in explaining the effects of physical activity on cognition and academic achievement, it seems vital to get a better understanding of how different types of physical activity affect children's brain activation patterns. This will greatly increase our understanding of the mechanisms that are underlying effects of physical activity on cognition and academic achievement.

6.1.1 PHYSIOLOGICAL MECHANISMS

Cognition entails a set of mental processes needed for perception, memory, and action, which include, amongst others, attention and executive functioning (Donnelly et al., 2016). Most of the studies examining effects of physical activity on cognition have provided evidence for the beneficial effects of aerobic physical activity at a moderate-to-vigorous intensity level (MVPA; see Donnelly et al., 2016). According to physiological mechanisms, this type of physical activity in the short-term, after one bout, leads to an upregulation of neurotransmitters (e.g. dopamine, monoamine, brain-derived neurotrophic factors). After more frequent participation in physical activity over several weeks, this facilitates structural and functional adaptations of the brain due to, amongst others, angiogenesis and neurogenesis in brain areas that support cognitive performance (see Best, 2010).

Only few studies have examined the physiological mechanisms by looking at effects of longitudinal aerobic physical activity on children's brain activation. These studies focused on brain activation patterns during tasks measuring one specific aspect of cognition, namely inhibition. In one of the first of these studies, Davis and colleagues (2011) implemented a 13-week aerobic physical activity intervention after school for sedentary, overweight children. As a result of the intervention, they found increased prefrontal cortex activity and reduced posterior parietal cortex activity during an antisaccade task, as well as improvements in the planning aspect of executive functioning and mathematics achievement. Krafft and colleagues (2014) examined an 8-month aerobic after-school program in overweight children, which resulted in decreased activation during an antisaccade task in several regions known to be related to anti-saccade performance (e.g. inferior frontal gyrus and anterior cingulate cortex), and increased activation in regions supporting cognitive control (e.g. superior frontal, medial frontal, middle frontal, and cingulate gyri). Chaddock-Heyman and colleagues (2013) implemented a 9-month after-school physical activity program aimed at improving children's aerobic fitness, which was found to result in significant decreases in activity in the right anterior prefrontal cortex during a Flanker task. These changes were mainly driven by decreased activation during incongruent trials, which are complex trials requiring the most inhibitory and attentional abilities. The pattern of brain activation in the physical activity group was similar to that of young adults, leaving the authors to suggest that less activation during a complex inhibition task reflects more mature brain function (Chaddock-Heyman et al., 2013).

6.1.2 COGNITIVE STIMULATION MECHANISM

Other studies have brought forth the cognitive stimulation hypothesis, in which it is argued that physical activity that is cognitively-engaging is even more beneficial for cognition and brain development than aerobic physical activity containing 'simple', repetitive exercises (Pesce, 2012). Cognitive engagement refers to the amount of cognitive effort and attention that is needed to participate in a certain activity or to master a certain skill (Tomporowski, McCullick, Pendleton, & Pesce, 2015). Cognitively-engaging physical activity entails activities that require a high amount of cognitive effort to understand new information, such as complicated rules; and activities in which complex motor skills have to be practiced, such as multi-limb coordination and strategic games (Tomporowski et al., 2015). This type of physical activity is thought to partly activate the same brain areas as those used during cognitive tasks, thereby promoting the development of these brain areas, consequently aiding cognitive performance as well (Diamond & Lee, 2011). In a recent meta-analysis, promising effects on executive functioning and academic achievement were found for this type of physical activity, with seemingly even stronger effects than aerobic physical activity (de Greeff et al., 2018a). The cognitive stimulation hypothesis is relatively new, and we are not aware of studies that have examined the effects of cognitively-engaging physical activity on the brain.

Some studies in older adults have examined the effects of coordinative physical activity (see Voelcker-Rehage & Niemann, 2013 for a review). Coordinative physical activity comprises exercises that require gross and fine motor coordination, such as eye-hand coordination, spatial orientation, and balance (Voelcker-Rehage, Godde, & Staudinger, 2011). Coordinative physical activity shows considerable overlap with cognitively-engaging physical activity, in that both require the involvement of complex motor skills and higher-order cognitive processes, such as attention. In the review by Voelcker-Rehage and colleagues (2011), it was concluded that the acquisition of new skills during coordinative physical activity is related to increased activation in the prefrontal and parietal cortex. With repeated execution of a newly learned skill, activity in the frontal cortex decreases, and activity becomes more focalized and more efficient, possibly reflecting automatization of the newly learned skill. It is unclear how these changes in brain activation relate to cognitive performance however.

6.1.3 DIFFERENT TYPES OF PHYSICAL ACTIVITY

Following the physiological mechanisms and cognitive stimulation hypothesis described earlier, it is likely that the mechanisms by which physical activity affects cognition and academic performance differ depending on the type of physical activity involved. In line with this assumption, animal studies have revealed that different types of physical activity affect the brain in a different manner (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990). Aerobic training has been found to result in, for example, the formation of new blood vessels from existing blood vessels (angiogenesis), the development of new neurons (neurogenesis), and the plasticity of neurotransmitter systems, whereas coordinative activities lead to pruning and restructuring of synapses (synaptogenesis).

Also in humans, it has been argued that different types of activities (i.e. aerobic compared to coordinative exercise) differ in underlying brain changes (Voelcker-Rehage & Niemann, 2013). Only one study has made a direct comparison between the effects of different types of physical activity on brain activation however, examining the effects of cardiovascular and coordination training on cognition and brain activation in older adults (Voelcker-Rehage et al., 2011). It was found that both types of physical activity led to improved executive functioning, coupled with decreased activation in the prefrontal areas in both intervention groups, reflecting more efficient information processing. In addition, specific effects were found for the different training programs. Decreased activation was found in the sensorimotor network (i.e. several superior, middle, and medial frontal, superior, and middle temporal cortical areas) for the aerobic intervention group. In the coordination training group, increased activation was found in the visual-spatial network (i.e. inferior frontal gyrus, and superior parietal lobule) as well as in subcortical structures that are considered to be important for process automatization (i.e. the thalamus and caudate body). Based on these results it was concluded that the mechanisms by which physical activity affects cognition depend on the type of activity involved. No studies have yet examined whether distinct types of physical activity differently target brain activation in children as well.

6.1.4 THE PRESENT STUDY

Only few studies have examined the effects of aerobic physical activity on children's brain activation. Further, the few studies that did only measured brain activation patterns during inhibition tasks. Although inhibition is an important cognitive skill, these results do not directly translate to other cognitive functions, such as working memory, because different brain areas are underlying inhibition and working memory (Best & Miller, 2010). In addition, inhibition and working memory have different developmental patterns, with inhibition being already quite well developed by the early school years, whereas working memory performance shows growth into late adolescence (Best & Miller, 2010). Further investigation of the effects of physical activity on working memory-related brain activation patterns thus seems vital. In addition, to our knowledge, the effects of cognitively-engaging physical activity on children's brain activation have not yet been examined, and no studies have directly compared changes in children's brain activation as a result of different types of physical activity. This is unfortunate, as childhood is a critical period in which the brain shows substantive development. Physical activity might provide an effective means for stimulating children's brain development, possibly having long-term beneficial effects on cognitive and academic performance.

Therefore, the present study aims to examine how different types of physical activity affect children's brain activation during a visuospatial working memory task. As the strongest evidence base has been built for aerobic physical activity, and considering the promising effects of cognitively-engaging physical activity in stimulating children's cognitive and academic development, the focus will be on those two types of physical activity. Different effects on brain activation are expected for the two physical activity interventions. The effects of both interventions are expected to be the most pronounced for the prefrontal areas, as these are found to be underlying visuospatial working memory performance (see Wager & Smith, 2003), and as previous studies have consistently found effects of physical activity on brain activation in these areas (see Donnelly et al., 2016). Results of this study will increase our understanding of how different types of physical activity affect the brain, thereby providing useful information for the development of effective physical activity interventions for improving children's cognitive and academic development.

6.2 METHODS

6.2.1 DESIGN

This study is part of a large cluster randomized controlled trial at 22 primary schools in the Netherlands (*n* = 891 children) examining the effects of two different types of physical activity interventions on children's physical fitness, motor skills, cognition and academic achievement (see Chapter 5 for an elaborate description of the project design). At each school a third and a fourth grade class participated, of which one class was randomly assigned as intervention group, following four intervention lessons per week. The other class was the control group, following their regular physical education program of two lessons per week. Parents from participating children could voluntarily sign-up their child for the MRI sub-study. Only children over 8 years that had no contraindications for MRI were included. An inclusion protocol was followed to ensure that children were equally sampled over grades, conditions (control, aerobic intervention, cognitively-engaging intervention) and schools, and to ensure that boys and girls were equally represented. If the number of eligible students that signed up exceeded the number of slots that had to be filled, it was randomly decided which child could participate. There were deviations from the inclusion protocol in case the number of children that met the inclusion criteria could not be met. As a solution, some schools are oversampled in the study, whereas others are underrepresented. The inclusion protocol and deviations from this protocol can be found in Appendix 10.

6.2.2 PARTICIPANTS

Ninety-two children (47 girls, 51.1%) participated in this study. Children were in grade 3 (*N* = 46, 50%) and grade 4 and had mean age of 9.14 years (*SD* = .63). Nine children dropped-out at posttest because of logistic problems (e.g. planning of scan time) or personal reasons, leaving 83 children who were scanned at both pretest and posttest. Twenty-one children were excluded from further analyses due to low quality of the data (see image analyses). An overview of the included and excluded children in the three groups at each stage of the study can be found in Appendix 10. Descriptive statistics of the final number of included children (*n* = 62) are presented in Table 6.1. Children in the three groups did not significantly differ on age ($F(2, 59) = 1.44$, $p = .24$), socioeconomic status (SES; $F(2, 59) = .32$, $p = .73$), gender ($\chi^2(2) = .51$, $p = .78$), grade ($\chi^2(2) = 2.55$, $p = .28$), or BMI classification ($\chi^2(4) = 5.48$, $p = .24$). Children's parents or legal guardians provided written informed consent. This study was approved by the ethical board of the Vrije Universiteit Amsterdam (Faculty of Behavioural and Movement Sciences) and is registered in the Netherlands Trial Register (NTR5341).

TABLE 6.1. Baseline characteristics of children included in the analyses, for the total sample and separately for the control group, aerobic intervention group and cognitively-engaging intervention group.

	Total sample (*n* = 62)	Control group (*n* = 17)	Aerobic intervention group (*n* = 22)	Cognitively-engaging intervention group (*n* = 23)
Grade, n grade 3 (%)	28 (45.2)	5 (29.4)	12 (54.5)	11 (47.8)
Gender, n boys (%)	30 (48.4)	7 (41.2)	11 (50.0)	12 (52.2)
Age, in years (SD)	9.2 (0.6)	9.37 (0.5)	9.2 (0.7)	9.0 (0.6)
SES[a] (SD)	4.6 (1.1)	4.6 (.9)	4.7 (1.0)	4.5 (1.4)
BMI[b] n non-overweight (%)	53 (88.3)	17 (100)	19 (90.5)	17 (73.9)
BMI n overweight (%)	6 (10.0)	-	2 (9.5)	4 (17.4)
BMI n obese (%)	1 (1.7)	-	-	1 (4.3)

Note: [a.] SES = socioeconomic status; measured with a parental questionnaire. Level of parental education ranged from no education (0) to postdoctoral education (7; Schaart, Mies, & Westermann, 2008). Mean level of education of both parents was calculated, or, in case only one of the parents' educational level was specified, this was used as measure of SES. [b.] BMI category was determined based on the international classification values by Cole and Lobstein (2012). BMI data was missing for two participants.

6.2.3 MATERIALS

IMAGING TASK

The Spatial Span task (van Ewijk et al., 2014; 2015), an adapted version of a task developed by Klingberg, Forssberg, and Westerberg (2002), was used as a measure of visuospatial working memory. The task was implemented in E-prime (Psychology Software Tools, version 2.0.10.356). In the Spatial Span task, a 4 x 4 grid was presented on a screen behind the MRI scanner that was visible for the child via a mirror attached to the head coil. In the grid, a sequence of either three (low memory load) or five (high memory load), yellow (working memory) or red (baseline) circles were presented for 500 ms each, with an inter-stimulus interval (empty grid) of 500 ms. Following this sequence, a probe consisting of a number and a question mark was presented in one of the 16 boxes in the grid. In the working memory trials, children were instructed to remember the order in which the circles were presented and, when the probe was shown, had to indicate with a right ('yes') or left ('no') button press whether the probe location matched the location of the stimulus that was indicated by the probe number. Children were instructed to respond within 2000 ms. During baseline trials (red circles), three or five circles were shown in a predictable manner in the four corners of the grid and were always followed by a probe with the number 8. Children were instructed to look at the circles, but not to remember their order, and to always press 'no' when the probe appeared. Feedback was provided in both conditions via a green (correct response) or red (incorrect response) coloured bar underneath the probe. The task consisted of four blocks each containing 24 trials, with a short break in between blocks, resulting in a total task duration of approximately 16 minutes. The percentage of the correct working memory trials (for the low and high working memory load trials separately, and for the low and high working memory load trials combined) were used as outcome measures for behavioral performance. A schematic overview of the task is presented in Figure 6.1.

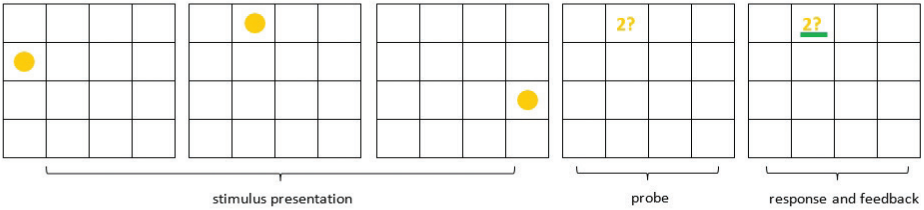

FIGURE 6.1. Schematic overview of a low working memory load trial of the spatial span task (van Ewijk et al., 2015). In this example trial, a sequence of three (low load) yellow (working memory) circles was presented (stimulus presentation). Next, a probe appeared, prompting whether the third circle appeared in that specific box of the grid. In this example, 'yes' was the correct answer (the second circle was in the position indicated by the number two). A green bar was presented underneath the probe as feedback, because a correct response was given (response and feedback).

6.2.4 PROCEDURE

Two fourteen-week intervention programs, each consisting of four lessons per week (56 lessons in total), were developed by Physical Education teachers and Human Movement Sciences researchers. One intervention focused on aerobic physical activity, the other on cognitively-engaging physical activity. An elaborate description of the intervention programs can be found in Chapter 5.

Children in the intervention groups received four intervention lessons each week for 14 weeks, during regular and extra physical education lessons, thereby doubling the number of lessons children received. Lessons were delivered by hired physical education teachers who were familiarized with the interventions in a training session and via a detailed manual. Children in the control groups followed their regular physical education program, participating in two lessons each week, which were provided by their own teacher. Children participated in the MRI protocol in the two weeks before the start of, and the two weeks after the intervention program.

Children were familiarized with the scanner and the task in a half hour session before the real scanning at pretest, using a mock scanner and a laptop. Children responded to the task by using a button-box (Current designs Inc., Philadelphia, USA) which was connected to the computer. Head movements were minimized by inserting small, wedge-formed pillows between the head coil and the child's head. Children received a small present and a copy of their structural T1-weighted scan after the posttest.

6.2.5 IMAGE ACQUISITION

The imaging protocol was carried out at two different sites (Amsterdam and Groningen) on either a 3 Tesla whole-body unit (Discovery MR750, GE Healthcare, Milwaukee, Wisconsin; Amsterdam) or a 3 Tesla Philips Intera scanner (Philips Medical Systems, Best, the Netherlands; Groningen), using a 32-channel head coil and closely-matched acquisition parameters. Four runs with T2*-weighted functional gradient echo-planar images (EPI) were acquired using the following parameters: repetition time (TR) = 2000 ms, echo time (TE) = 35 ms, flip angle (FA) = 80°, field of view (FOV) = 211 mm, slice thickness = 3.0 mm, interslice distance = 0.3 mm, 135 dynamics, and 64 x 64 grid (Amsterdam protocol), or 64 x 60 grid (Groningen protocol), voxel size = 3.3 x 3.3 x 3.3 mm. Two spin echo EPI scans with opposing polarities of the phase-encode blips were acquired (TR =6000 ms, TE = 60 ms, all other parameters remained the same) which would later be applied to correct for distortions in the functional images caused by the susceptibility distribution of the subject's head (Andersson & Sotiropoulos, 2016; Smith et al., 2004). Additionally, high resolution, whole-brain T1-weighted sagittal brain images were acquired at the beginning of the scan protocol (TR = 400 ms, TE = min full, FA = 111°, FOV = 250 mm, slice thickness = 3.0 mm, interslice distance = 0.3 mm, and 256 x 192 grid, voxel size = 1 x 1 x 1 mm).

6.2.6 IMAGE ANALYSES

Preprocessing (see Chapter 4) was carried out in FLS feat (FMRI Expert Analysis Tool; FMRIB Analysis group, Oxford, UK). The same preprocessing procedure was followed for the pretest and the posttest data. In the first-level analysis, two contrasts of interest were set-up in FSL: one contrasting working memory to control (*mean working memory*), and one contrasting high working memory load to low working memory load (*load difference*). The brain activation patterns associated with these contrasts are presented in Chapter 4. Consequently, a difference image was constructed by subtracting the pretest contrast image from the posttest contrast image in SPM 12.0 (SPM 12.0 v6470, running in MATLAB 2017b), resulting in a contrast image showing changes in brain activation between pretest and posttest. Registration was conducted using affine transformations in FLIRT. These images were consequently used for statistical analyses (see Chapter 4) in SPM 12.0.

6.2.7 ANALYSES

Initial differences in performance on the spatial span task between the three groups were examined in IBM SPSS Statistics 25.0 using Analysis of Variance (ANOVA) and post-hoc analyses with Bonferroni-correction.

MAIN ANALYSES

First, for both contrasts whole brain activation differences between pretest and posttest across all groups were analyzed in a flexible factorial model in SPM 12.0, by adding the pretest contrast maps and posttest contrast maps for each child. The aim of this analysis was to examine whether there were overall differences in brain activation between pretest and posttest. Following, an analysis was conducted to examine interactions between condition and time, that is: whether the three groups (control group vs. aerobic intervention vs. cognitive intervention) showed differences in activity changes between pre- and posttest. Difference maps representing changes in activation between pretest and posttest were entered in a flexible factorial model. A covariate of interest representing intervention group (aerobic intervention group, cognitively-engaging intervention group, control group) was added to this model, and site was included as covariate of no interest, because differences between scan sites were found (see Chapter 4). Results that survived the cluster level significance of $p < 0.05$, family wise error (FWE) corrected, initial threshold $p < 0.001$, will be presented.

ADDITIONAL ANALYSES

Additionally, exploratory analyses were performed by applying a scaled subprofile model/principal component analysis (SSM/PCA) method (Moeller, Strother, Sidtis, & Rottenberg, 1987). We used this method to obtain differences in brain activation patterns between two study groups (i.e. aerobic intervention vs. control, cognitively engaging intervention vs. control, aerobic intervention vs cognitively engaging intervention). The SSM/PCA method has been used extensively with positron emission tomography (PET) data to identify brain activation patterns that can distinguish patient populations from healthy controls (e.g. Mudali et al., 2015, 2016; Teune et al., 2013, 2014; also see Alexander & Moeller, 1994). SSM/PCA analysis is thought to provide greater statistical power than more traditional mass univariate approaches (Alexander & Moeller, 1994).

The SSM/PCA method was implemented in-house in MATLAB. The preprocessed difference maps - representing changes in activation between pretest and posttest - were used as input. Several steps were followed. First, a gray matter mask was applied to include only gray matter voxels in the analyses. Second, the mean activity pattern of the reference group was subtracted from the activity pattern of each subject to remove activity offset. Third, the multivariate principal component analysis (PCA) based algorithm was used to reduce the complexity of the multivariate data; those principal components (PCs) were retained that, together, explained (at least) 50 % of the variance. Fourth, a subject score was calculated representing the degree to which a PC was present for each subject. Fifth, to calculate an intervention pattern, a stepwise logistic regression was performed to select and combine the PCs into one intervention pattern (e.g. the deviations in the activity pattern of the intervention group from the activity pattern from the reference group). Sixth, bootstrapping (N = 1000 bootstraps) was applied to check the stability of the brain activation patterns extracted by the SSM/PCA. This bootstrapping method resulted in images revealing brain areas with values that were not zero in 90% of the bootstraps. Last, a leave-one-out cross-validation (LOOCV) was conducted to examine whether the pattern extracted by the SSM/PCA could be used to classify individual children. For each child, the SSM/PCA analysis was conducted once without its data being taken into account[1]. Following, the results of this analysis (i.e. the activity pattern obtained when comparing two groups) were used to investigate the extent to which the intervention pattern

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[1] For the calculation of the GMP, all children were included as the control group had a small number of children and the GMP was not stable when one child was removed from the data to calculate GMP.

existed for this child. As children in the different study conditions were expected to differ from each other, it was expected that, on average, activity patterns in the intervention groups would diverge from children in the reference group. If a child's original group membership can be reliably traced back from the pattern extracted by the SSM/PCA, this provides support for the validity of the extracted activity pattern.

The SSM/PCA method and LOOCV were applied three times to compare the three groups: 1) aerobic intervention group vs. control group, 2) cognitively-engaging intervention group vs. control group, and 3) cognitively-engaging intervention group vs. aerobic intervention group. Intervention-related activity patterns were extracted with both positive (increases in activation) and negative (decreases in activation) voxel loadings. A description of the SSM/PCA and LOOCV method that was used can be found in Appendix 11. More information on the theoretical assumptions of and the analysis steps taken in a SSM/PCA can be found elsewhere (Alexander & Moeller, 1994; Moeller et al., 1987).

In the results section, Figures are presented showing the brain areas where increases or decreases in brain activation differed in 90 % of the bootstraps when comparing the reference group and the intervention group. Tables are presented with the labels and locations of the brain areas where meaningful differences in brain activation were found. Tables with an overview of all brain regions where differences were found (also those that did not seem meaningful) are shown in Appendix 12. Lastly, the results of the LOOCV are presented, showing the extent to which an individual's brain activation pattern fitted the results obtained by that individual's LOOCV.

6.3 RESULTS

6.3.1 BEHAVIORAL RESULTS

Mean scores on the Spatial Span task at pretest and posttest for the three groups are presented in Table 6.2. At pretest, the three groups did not significantly differ in performance on the spatial span task (F (2, 59) = .15, p = .86). Overall, children performed better at posttest than at pretest (F (1, 59) = 12.32, p < .001). There was no significant interaction between condition and time (F (2, 59) = 1.08, p = .35), indicating that the improvement between pretest and posttest did not differ between the three groups.

TABLE 6.2. Average pretest and posttest scores on the visual span task (percentage working memory trials correct) and corresponding standard deviations for the three conditions.

	n	Control group	*n*	Aerobic intervention group	*n*	Cognitively-engaging intervention group
Pretest	17	69.2 (3.8)	22	66.8 (3.3)	23	66.9 (3.2)
Posttest	17	76.5 (3.8)	22	73.8 (3.3)	23	69.2 (3.3)

6.3.2 FMRI RESULTS

The mean activation pattern for the *mean working memory* contrast, over both scanning sessions and for all groups, is presented in Chapter 4. This activation pattern is largely in line with what was found in previous studies, supporting the validity of the task. There was no significant activation associated with *load difference* (see Chapter 4). Consequently, this contrast was not further examined.

First, mean activation differences between pretest and posttest for all groups together were analyzed to see whether brain activation patterns changed over the fourteen weeks. No significant activation changes were found between pretest and posttest (all $p > .05$).

Second, time-by-group interactions were examined to investigate intervention effects. No significant differences in activation changes were found between the three groups (all $p > .05$), indicating that the interventions did not result in changed brain activation patterns.

ADDITIONAL ANALYSES

A SSM/PCA method was applied to examine which activity patterns could be obtained when comparing the three groups.

Aerobic intervention group vs. control group

First, a SSM/PCA was applied to examine which activity patterns could be obtained when comparing the aerobic intervention group to the control group. Less activation in areas in the frontal cortex (left inferior gyrus, left superior middle frontal gyrus and medial frontal lobe), the occipital cortex (right middle and lateral occipital gyri), and the parietal cortex (angular gyrus) was found in the aerobic intervention group as compared to the control group (see Table 6.3 and Figure 6.2).

TABLE 6.3. Brain areas obtained when comparing the pretest-posttest differences maps of the aerobic intervention group and the control group. The control group was used as the reference category.

		MNI coordinates[a]		
Anatomical label(s)	Hemisphere	x	y	z
Deactivation[b]				
Inferior frontal gyrus	Left	-48	28	-6
Superior middle frontal gyri/medial frontal lobe	Left	-26	58	-2
Medial & lateral occipital gyri	Right	8	-80	-10
Angular gyrus	Left	-54	-50	12

[a] Brain coordinates defined by the Montreal Neurological Institute (MNI), based on which the location of (de)activated clusters of voxels can be identified. [b] Brain areas showing deactivation in the aerobic intervention group as compared to the control group.

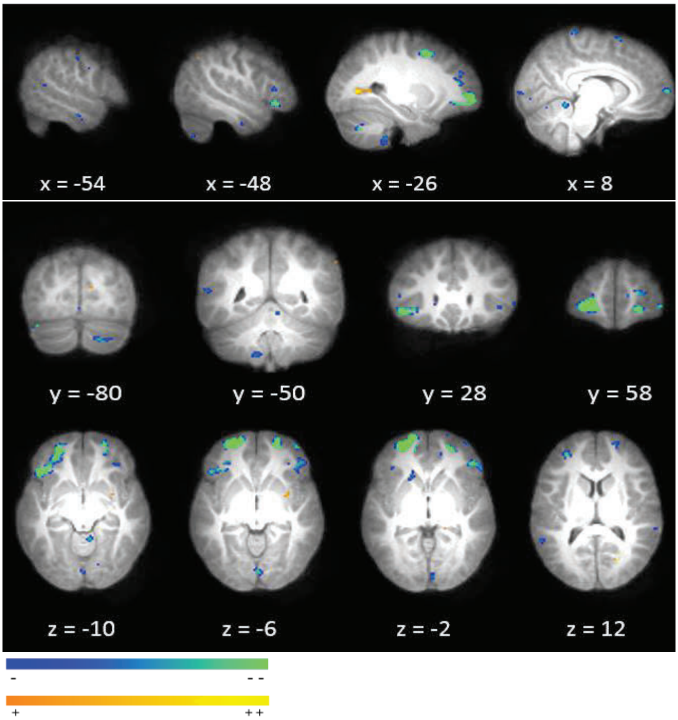

FIGURE 6.2. Results of the bootstrapping analysis revealing brain activation patterns obtained when comparing the aerobic intervention group to the control group. Slices showing the (de)activated brain regions are presented, with a sagittal (upper), coronal (middle) and axial (lower) view. Warm colours represent increases in activation; cool colours represent decreases in activation.

Following, a LOOCV was conducted as a validation of the results of the SSM/PCA, examining whether group membership of individual children could be predicted based on their brain activation pattern. Results of this analysis are presented in Figure 6.3. Results were unstable due to large inter-individual variability, which negatively influences the reliability of these results. The LOOCV shows that children in the aerobic intervention are not distinguishable from children in the control group (values for both groups are around 0).

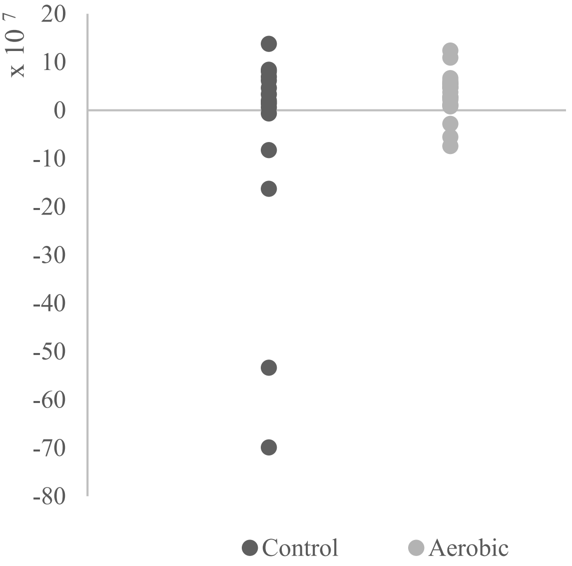

FIGURE 6.3. Results of the LOOCV contrasting the aerobic intervention group and the control group. The y-axis represents the deviation in the individual's activity pattern from the activity pattern of the reference group (i.e. control group).

Cognitively-engaging intervention group vs. control group

A second SSM/PCA was applied to examine which activity patterns could be obtained when comparing the cognitively-engaging intervention group to the control group. The cognitively-engaging intervention group showed deactivation in frontal areas (bilateral in the superior middle frontal gyri, medial frontal lobe and the inferior frontal gyrus, left in the supplementary motor area and the premotor cortex), and occipital areas (right medial/lateral occipital gyri) as compared to the control group. Activation in occipital areas (right primary visual cortex), parietal areas (bilateral angular gyrus) and the cingulate gyrus was found in the cognitively engaging group compared to the control group (Table 6.4 and Figure 6.4).

TABLE 6.4. Brain areas obtained when comparing the pretest-posttest differences maps of the cognitively-engaging intervention group and the control group. The control group was used as the reference category.

		MNI coordinates[a]		
Anatomical label(s)	Hemisphere	x	y	z
Deactivation[b]				
Superior middle frontal gyri/ middle frontal lobe (BA10; Prefrontal Cortex)	Left	-20	60	2
	Right	24	56	-6
Inferior frontal gyrus	Left	-44	28	-8
	Right	48	36	-4
Supplementary motor area (SMA), premotor cortex	Left	-22	14	48
Superior middle frontal gyri/ medial frontal lobe (BA8)	Right	40	12	52
Medial/lateral occipital gyri	Right	24	-84	-18
Activation[c]				
Primary visual cortex	Right	24	-70	6
Cingulate gyrus	Right	16	-58	22
Angular gyrus	Right	52	-56	44
	Left	-50	56	42

[a.] Brain coordinates defined by the Montreal Neurological Institute (MNI), based on which the location of (de)activated clusters of voxels can be identified. [b.] Brain areas showing deactivation in the cognitively-engaging intervention group as compared to the control group. [c.] Brain areas showing increased activation in the cognitively-engaging intervention group as compared to the control group.

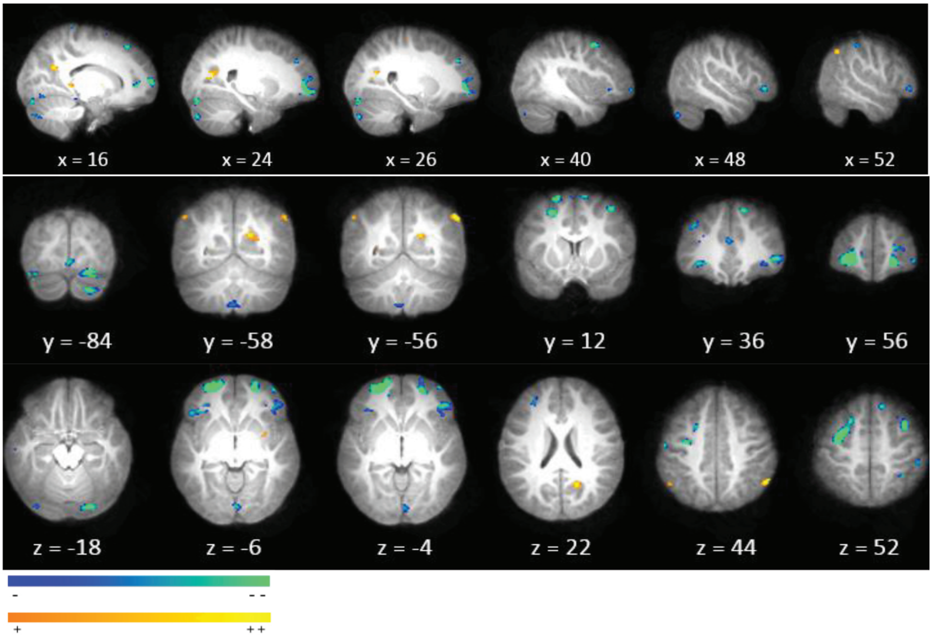

FIGURE 6.4. Results of the bootstrapping analysis revealing brain activation patterns obtained when comparing the cognitively-engaging intervention group to the control group. Slices showing the (de)activated brain regions are presented, with a sagittal (upper), coronal (middle) and axial (lower) view. Warm colours represent increases in activation; cool colours represent decreases in activation.

A LOOCV was then conducted to cross-validate these results by examining whether group membership of individual children could be predicted based on their brain activation pattern. Results of this analysis are presented in Figure 6.5. Again, results of this analysis were unstable due to large inter-individual variation. This visual representation suggests that there is more variation in the deviations from the reference activity pattern, with slightly more positive deviations in the cognitively-engaging intervention group than in the control group, where the pattern of deviation is more focused.

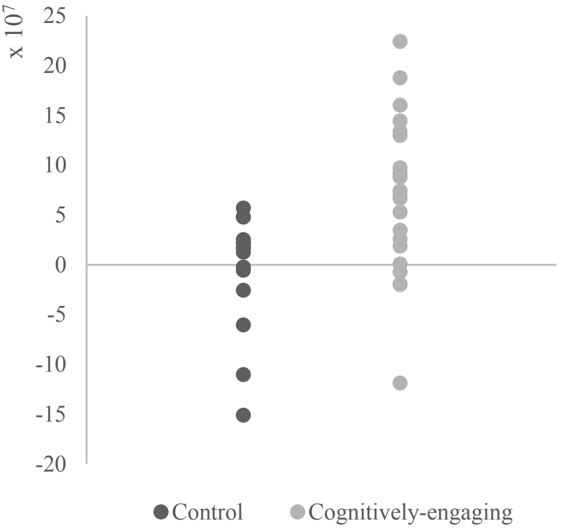

FIGURE 6.5. Results of the LOOCV contrasting the cognitively-engaging intervention group and the control group. The y-axis represents the deviation in the individual's activity pattern from the activity pattern of the reference group (i.e. control group).

Aerobic intervention vs. cognitively-engaging intervention

Lastly, a SSM/PCA was used to examine which brain activation patterns could be obtained when comparing the two intervention groups. Children in the cognitively-engaging intervention group showed deactivation in temporal areas (right middle and inferior temporal gyri) and frontal areas (left supplementary and premotor cortex) as compared to children in the aerobic intervention group. Activation was found in occipital areas (bilateral medial and lateral occipital gyri), parietal areas (right superior parietal gyrus), and bilateral in the thalamus and cingulate gyrus in the cognitively-engaging group compared to the aerobic intervention group (Table 6.5, Figure 6.6).

TABLE 6.5. Brain areas obtained when comparing the pretest-posttest differences maps of the cognitively-engaging intervention group and the aerobic intervention group. The aerobic intervention group was used as the reference category.

		MNI coordinates[a]		
Anatomical label(s)	Hemisphere	x	y	Z
Deactivation[b]				
Middle & inferior temporal gyri	Right	58	-42	-14
Middle temporal lobe	Right	68	-16	-14
Supplementary motor area and premotor cortex	Left	-50	-8	30
Activation[c]				
Medial and lateral occipital gyri: Visual association cortex	Bilateral	0	-72	24
Superior parietal lobule	Right	14	-64	32
Thalamus	Right	10	-16	14
	Left	-8	-12	16
Cingulate gyrus	Bilateral	2	2	30

[a.] Brain coordinates defined by the Montreal Neurological Institute (MNI), based on which the location of (de)activated clusters of voxels can be identified. [b.] Brain areas showing deactivation in the cognitively-engaging intervention group as compared to the aerobic intervention group. [c.] Brain areas showing increased activation in the cognitively-engaging intervention group as compared to the aerobic intervention group.

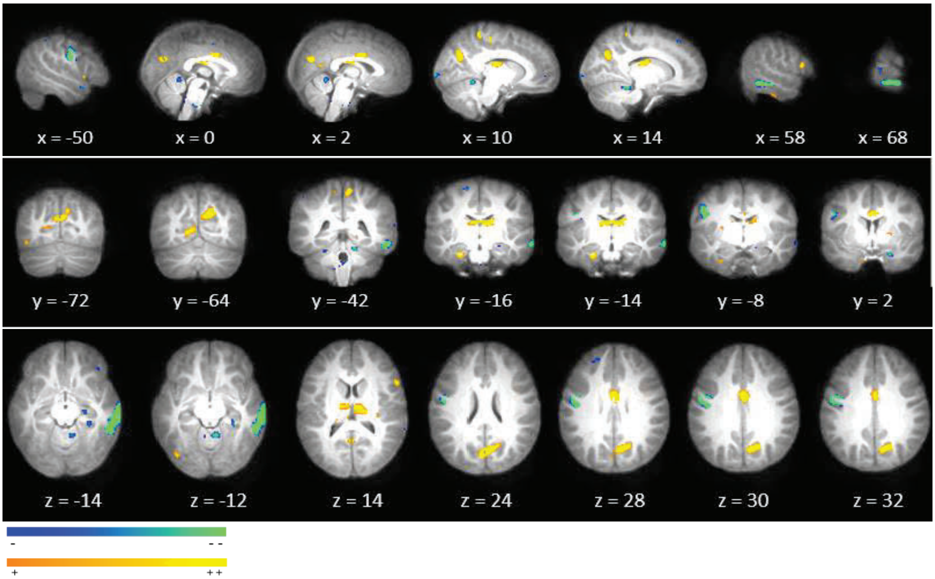

FIGURE 6.6. Results of the bootstrapping analysis revealing brain activation patterns obtained when comparing the pretest-posttest differences maps of the cognitively-engaging intervention group and the aerobic intervention group. Slices showing the (de) activated brain regions are presented, with a sagittal (upper), coronal (middle) and axial (lower) view. Warm colours represent increases in activation; cool colours represent decreases in activation.

A LOOCV was conducted to examine whether group membership of individual children could be predicted based on their brain activation pattern. Results of this analysis are presented in Figure 6.7. Again, results of this analysis were unstable due to large inter-individual variation. This visual representation suggests that children in the cognitively-engaging intervention group show more variation in their deviation patterns, with slightly more positive deviations compared to the reference activity pattern of children in the aerobic intervention group.

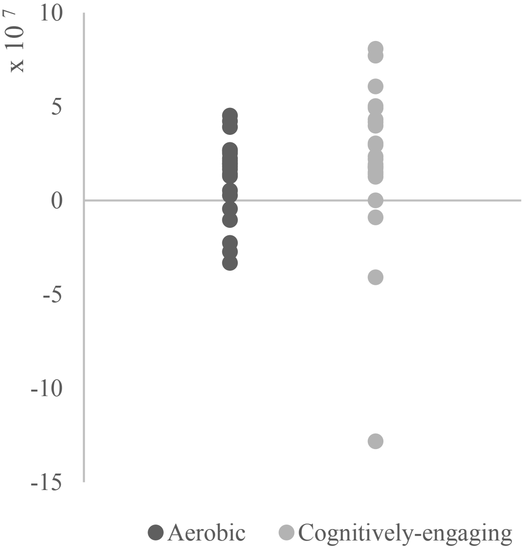

FIGURE 6.7. Results of the LOOCV contrasting the cognitively-engaging intervention group to the aerobic intervention group. The y-axis represents the deviation in the individual's activity pattern from the activity pattern of the reference group (i.e. aerobic intervention group).

6.4 DISCUSSION

This is the first study examining the effects of two different types of physical activity, aerobic and cognitively-engaging, on children's brain function during a visuospatial working memory task. We aimed to reveal mechanisms underlying effects of physical activity on cognition. No significant effects of the interventions on brain activation were found when using mass univariate analysis. This contradicts findings of previous studies that do report changes in children's brain activation as a result of long-term physical activity interventions (see Donnelly et al., 2016). This result is, however, in line with the non-significant effects that were found on the behavioral outcomes of the sample included in this study, and the total sample of the '*Learning by Moving*' project (on physical fitness and motor skills, van der Fels et al., subm.; cognition, de Greeff et al., 2018b; and academic skills, see Chapter 3). However, in additional, exploratory pattern analyses, brain activation patterns - consisting of activation differences in frontal, occipital, and parietal cortices - were obtained when comparing intervention effects for the three groups, with different patterns for the two physical activity intervention groups. This suggests that the aerobic and cognitively-engaging physical activity intervention programs differently affected children's brain activation. These results are discussed in more detail below.

6.4.1 BRAIN AREAS SUSCEPTIBLE TO CHANGE

Although further research is needed to substantiate the results of the pattern analyses, these provide useful indications for brain areas that might be susceptible to change as a result of different types of physical activity. In line with results of the few previous studies focusing on the effects of aerobic physical activity on children's brain activation (Chaddock-Heyman et al., 2013; Davis et al., 2011; Krafft et al., 2014), the results of our pattern analyses suggest that the effects of aerobic physical activity are most pronounced in the frontal and parietal areas. Physical activity is often expected to affect activity in the frontal, and especially prefrontal, regions, because these areas are important for executive functioning (Chaddock, Pontifex, Hillman, & Kramer, 2011), the cognitive functions that have found to be most strongly affected by physical activity (Donnelly et al., 2016). Although changes in frontal activity as a result of aerobic physical activity have previously been found, the direction of change is inconsistent across studies (Chaddock-Heyman et al., 2011; Davis et al., 2011; Krafft et al., 2014; Voelcker-Rehage, et al., 2011). The decreases in frontal activity that we obtained when comparing the aerobic intervention group to the control group are similar to the decreases in prefrontal cortex activity that were found as a result of a 9-month aerobic intervention by Chaddock-Heyman and colleagues (2013), and after an aerobic intervention program in older adults (Voelcker-Rehage et al., 2011). In contrast, other studies have reported increases in activity in (pre)frontal regions as a result of aerobic physical activity interventions in children (Davis et al., 2011; Krafft et al., 2014). In interpreting these inconsistent results, it should be noted that the studies by Davis and colleagues (2012) and Krafft and colleagues (2014) both specifically focused on overweight children. Further, although changes in the frontal lobe are consistently found, the exact brain areas in which changes are found differ per study, possibly reflecting the functional specificity of different regions in the frontal lobe. Besides changes in parietal and frontal activity, we found decreased activity in the occipital areas when comparing the aerobic intervention group to the control group. As changes in activity patterns are most likely to be found in brain areas that are involved in task performance, finding changes in occipital lobe activity was not surprising, because occipital areas are strongly involved in visuospatial working memory performance (van Ewijk et al., 2015).

When comparing the cognitively-engaging intervention group to the control group, decreases in activity in the frontal and occipital areas were found, together with increases in activity in the visual, parietal, and cingulate cortex. It is difficult to relate these findings to previous results, as no other studies have yet examined the effects of cognitively-engaging physical activity on children's brain activation. One study that examined the effect of coordinative physical activity concluded that the acquisition of new (motor) skills during this type of physical activity is associated with increased activity in frontal and parietal areas, reflecting the cognitive demand of learning a new skill. Over time, as a skill gets automatized and less cognitive engagement is needed, activity in the frontal regions reduces and overall activity gets less widespread, reflecting more efficient recruitment of the brain during task execution (Voelcker-Rehage & Niemann, 2013). The decreases in frontal lobe activity that we found can thus be an indication of more efficient brain activation as a result of automatization of complex skills. Again, the occipital lobe is strongly involved in task performance, making activity changes in this region more likely as well. Complementing these results, our study suggests that cognitively-engaging physical activity results in increased activity in the parietal and cingulate cortex.

6.4.2 DIFFERENTIAL EFFECTS OF THE TWO PHYSICAL ACTIVITY INTERVENTIONS

To get a better understanding of whether the two physical activity interventions differently affected children's brain activation patterns, a direct comparison between the two interventions groups was conducted. This analysis revealed intervention-specific results. Patterns consisting of decreased activity in temporal and frontal areas, and increased activity in occipital and parietal areas, thalamus, and cingulate cortex were obtained when comparing the cognitively-engaging intervention group to the aerobic intervention group, suggesting that the cognitively-engaging intervention had differential effects on brain activation compared to the aerobic intervention group. To our knowledge, only one study has directly compared the effects of different types of physical activity (aerobic and coordinative), although on older adults brain activation (Voelcker-Rehage et al., 2011). This study found differential effects in older adults' brain function as a result of the two types of physical activity. Coordination training resulted in, amongst others, increases in activity in the parietal areas (i.e. parts of the visual-spatial network) and the thalamus (considered important for process automatization). Our results are largely in line with these findings, finding differential effects of the two types of physical activity, with increased activity in the parietal areas and the thalamus.

Based on the results of our pattern analyses, it can be tentatively concluded that different types of physical activity affect children's brain differently. This suggests that there are different mechanisms underlying the effects of aerobic compared to cognitively-engaging physical activity on cognition and academic achievement. Unfortunately, due to the exploratory nature of our analyses, we were not able to further study this hypothesis by relating the differences in activity patterns between the three groups to cognitive task performance. As previous studies have not examined yet whether activity changes in the brain resulting from physical activity are correlated with improvements in task performance, we cannot conclude that brain activation changes provide the mechanism by which physical activity results in improved cognitive and academic performance. Finding out whether neural changes in response to physical activity interventions are linked to behavioral improvements thus is an important goal for future research.

A limiting side note should be made when interpreting the results of the pattern analyses. The results of the LOOCV were unstable, suggesting that there was large inter-individual variability in intervention effects. It proved to be difficult to use the brain activation patterns at a single subject level to reliably predict to which group individual children belonged. Therefore, our findings have to be interpreted with caution, and further research is needed to substantiate them. Still, the results provide interesting indications for future studies, as they show which brain areas might be susceptible to change as a result of different types of physical activity.

6.4.3 EXPLANATIONS FOR LACK OF OVERALL EFFECTS

By comparing the effects of two types of physical activity, the aim was to get a better understanding of *how* physical activity affects cognitive and academic performance. The two physical activity interventions that were implemented were closely related to the mechanisms that are used to explain the positive effects of physical activity on cognition and academic achievement. The aerobic intervention was based on physiological mechanisms, which assume that aerobic physical activity results in changes in brain structure and functioning as a result of physiological changes in the brain, such as an increase in growth factors and neurons. The cognitively-engaging intervention followed the cognitive stimulation hypothesis, which expects that cognitively-engaging physical activity activates the same brain areas as those used for cognitive tasks, thereby resulting in more efficient use of those areas. Neither of the interventions resulted in changes in brain activation when using mass univariate analysis, or in improved cognitive or academic achievement as previously reported (de Greeff et al., 2018b; and Chapter 3 of this dissertation), and large inter-individual variability in effects was found. It is therefore difficult to draw definite conclusions about the truthfulness of the two mechanisms. It can be questioned whether physical activity interventions should be different in content (i.e. type of activities; following the cognitive stimulation mechanism), or implemented in a different way (i.e. frequency, duration, or intensity of activities; following the physiological mechanisms) in order to result in changes in brain activation.

Alternatively, a combination of both mechanisms, thus physical activity that focuses on cognitively-engaging activities at a moderate-to-vigorous intensity level, might be needed to bring about changes in brain activation, and consequently improved cognitive and academic performance. This combined mechanism can also explain why we did not find overall effects of the interventions on brain activation, despite there being indications of changes that were brought about by the two interventions: the mechanisms by themselves might not be strong enough to bring about positive effects on the brain. Results of the behavioral study of the '*Learning by Moving*' project, examining effects on academic achievement, also provide suggestions for this supplementary mechanism (see Chapter 3). In line with this, a behavioral study showed that physical activity that combined aerobic and cognitively-engaging activities had stronger effects on executive functioning compared to both a regular physical education program, and a program only focused on aerobic physical activity (Schmidt, Jäger, Egger, Roebers, & Conzelmann, 2015). Physical activity that combines aerobic and cognitively-engaging physical activities thus seems a promising topic for future research, as it can be expected that this type of physical activity will have more pronounced effects on brain activation and, consequently, cognitive and academic performance.

6.4.4 STRENGTHS, LIMITATIONS, AND FUTURE RESEARCH

This renewing study is the first to reveal the effects of different types of physical activity on children's brain activation during a task for visuospatial working memory. A strength of this study was the extensive analysis protocol that was implemented. Not only regular analysis procedures were followed, but also exploratory analyses were implemented that, to our knowledge, have not yet been used in this line of research. Thereby we were able to reveal intervention effects that would not have been found when using regular analysis methods, while also taking into account the large inter-individual variability in intervention effects. Further strengths of this study include the large sample size, and the structured inclusion protocol that was followed in order to include a representative sample.

A first limitation is that the task that was used might have not been sensitive enough to pick up changes in brain activation patterns, thereby also providing an explanation for why no significant intervention effects were found when using mass univariate analysis. This idea is underlined by the fact that none of the children's background characteristics were related to brain activation during the task (see chapter 4). Based on previous studies it was expected that factors such as age, SES, or gender would be related to differences in visuospatial working memory related brain activation (e.g. Barriga-Paulino, Benjumea, Rodríguez-Martínez, & González, 2015; Schweinsburg, Nagel, & Tapert, 2005; Thomason et al., 2009; Zilles et al., 2016). None of these relations was found however, and even performance on the task itself (percentage of trials with a correct answer) was not related to brain activation pattern. Still, the task activity pattern that was found largely coincided with results of previous studies using the same task (van Ewijk et al., 2014; 2015), providing support for the validity of the visuospatial working memory task.

Alternatively, not the task itself, but the way it was implemented in the scan protocol could provide an explanation for the lack of relations with, and changes in VSWM-related brain activation. The active state fMRI scans that were taken were part of a larger MRI protocol lasting one hour, also including diffusion tensor imaging (DTI) and resting state fMRI. The active state fMRI scans used for the present study were taken in the last part of the protocol. It proved to be difficult for children to lay still for such a long time, resulting in high movement parameters for the active state fMRI scans. In order to filter out most of the movement-related brain activation, extensive preprocessing steps had to be taken, and a number of participating children had to be excluded. This could have had effects on the quality of the data, possibly resulting in data that were not sensitive enough to reveal differences between children.

Lastly, to minimize variability in brain activation patterns, only brain activation during correct trials was taken into account. This was a deliberate choice, aiming to ease the interpretation of brain activation differences. Yet, this could have influenced the results, especially since children reached a rather low percentage of correct performance (68% of correct trials at the pretest, 74% of correct trials at posttest), whereas the aim was to reach ceiling effects (i.e. a high percentage of correct performance). For future studies, it would be interesting to examine what happened during the incorrect and omission trials as well.

6.4.5 CONCLUSION

Neither an aerobic physical activity intervention program, nor a cognitively-engaging physical activity program resulted in significant changes in children's brain activation when using classical mass univariate analysis. More insightful results were provided by exploratory pattern analyses, which obtained different brain activation patterns when comparing the three groups, thereby providing suggestions for brain areas that might be susceptible to change as a result of different types of physical activity. Although more research is needed to substantiate these results, we tentatively conclude that physical activity interventions influence children's brain activation patterns during visuospatial working memory, with different effects depending on the type of physical activity used. This is an important outcome to elaborate upon in future research, as changes in brain activation are thought to be the mechanism by which physical activity affects children's cognitive and academic achievement.


7

GENERAL DISCUSSION

7.1 MAIN AIM OF THE DISSERTATION

The main aim of this dissertation was to examine the effects of two types of physical activity, aerobic physical activity and cognitively-engaging physical activity, on primary school children's academic achievement and brain activation. As a first step, the relations among physical, cognitive, and academic skills were explored, as well as the relations between physical skills and brain activation. These studies focused on: 1) the mediating role of executive functioning in the relation between physical fitness and low academic achievement; 2) the differential relations of aerobic fitness and motor skills with academic achievement in reading, mathematics, and spelling; and 3) the relations of aerobic fitness and motor skills with brain activation. Results of these studies were used to formulate hypotheses for the second part of the dissertation, in which the effects of an aerobic physical activity intervention and a cognitively-engaging physical activity intervention on academic achievement and brain activation were examined.

7.2 SUMMARY OF THE MAIN FINDINGS

Chapter 2 showed that physical fitness and executive functions were not independent predictors of low academic achievement, but that executive functions significantly mediated the relation between physical fitness and low mathematics and spelling achievement. This mediating relation was found to be specific for the two academic domains examined. In mathematics, verbal working memory and visuospatial working memory mediated the relation between physical fitness and academic achievement, whereas in spelling only verbal working memory was a significant mediator.

In Chapter 3, the specific relations of aerobic fitness and motor skills with academic achievement in the domains of reading, mathematics, and spelling were examined. Motor skills were found to be a significant predictor of overall academic achievement, whereas aerobic fitness was not. However, when academic achievement was separated into reading, mathematics and spelling, the relations of aerobic fitness and motor skills were found to be specific for the distinct domains. Motor skills significantly predicted mathematics and spelling achievement, whereas aerobic fitness was a predictor of mathematics and reading achievement.

Chapter 4 describes children's brain activation pattern during a visuospatial working memory task (measured with functional MRI), and its relations with aerobic fitness and motor skills. Performance on a visuospatial working memory task was associated with increases in brain activation in the angular gyrus (right hemisphere) and superior parietal cortex (bilateral), coupled with deactivation in the inferior and middle temporal gyrus (bilateral). This task-activation pattern largely coincides with results of previous studies. Surprisingly, aerobic fitness and motor skills were not predictive of working memory related brain activation.

The effects of two physical activity interventions on academic achievement are described in Chapter 5. One intervention focused on aerobic physical activity, aiming to improve aerobic fitness via exercises at a moderate-to-vigorous intensity level, the other on cognitively-engaging physical activity, challenging both motor skills and cognition via games and exercises with complex rules or movements. The interventions did not have significant effects on academic achievement in reading, mathematics, or spelling. The volume of moderate-to-vigorous physical activity (MPVA) was found to be important, as a higher volume of MVPA resulted in better mathematics achievement at the posttest for both intervention groups, and better posttest spelling achievement for the cognitively-engaging intervention group specifically. In addition, pretest achievement was taken into account in examining the intervention effects, showing that lower-achieving children in reading benefited more from the cognitively-engaging intervention, with higher posttest reading achievement compared to lower-achievers in the control group.

In Chapter 6, the effects of the two physical activity interventions on brain activation during a visuospatial working memory task are presented. The interventions did not result in significant changes in overall brain activation. However, there were indications of differences in brain activation patterns – mainly in frontal, occipital, and parietal regions - that were obtained when comparing the intervention groups to the control group, suggesting that the interventions did have an effect on task-related brain activation. Further, intervention-specific differences were found when comparing the two intervention groups. The results were instable however, because of large inter-individual variability in intervention effects. Although we have to be cautious with drawing strong conclusions based on these results, they do provide suggestions of brain areas that are susceptible to change as a result of physical activity interventions. We tentatively conclude that physical activity interventions have an effect on children's brain activation, with different effects depending on the type of activity used.

7.3 GENERAL DISCUSSION

7.3.1 RELATIONS BETWEEN PHYSICAL, COGNITIVE, AND ACADEMIC SKILLS

This dissertation confirms the previously found relations between the physical, cognitive, and academic domain (de Greeff et al., 2018a; Santana et al., 2016). Both (aerobic) physical fitness (Chapters 2 and 3) and motor skills (Chapter 3) were found to be predictive of academic achievement. Moreover, results of this dissertation provide a better insight into these relations by showing that they are specific, meaning that different relations were found for the distinct academic domains. In Chapter 2, specific mediating relations of the distinct executive functions in the relation between physical fitness and academic achievement were found for the domain of mathematics, compared to the domain of spelling. In line with this, in Chapter 3 it was shown that the relations of aerobic fitness and motor skills with academic achievement differed depending on the academic domain involved.

The results presented in Chapter 2, where executive functions were found to be mediators in the relation between the physical and the academic domains, can provide an explanation for the specific relations between aerobic fitness, motor skills, and academic achievement in reading, mathematics, and spelling that are presented in Chapter 3. The executive functions needed for good performance in one academic domain (e.g. mathematics), differ from those needed in another domain (e.g. reading or spelling; Lubin, Regrin, Boulc'h, Pacton, & Lanoë, 2016). It can consequently be hypothesized that the link between aerobic fitness and reading needs to be explained by a closer relation between aerobic fitness and the executive functions needed for reading, whereas motor skills are probably more closely related to the executive functions needed in spelling. This hypothesis has not been examined, but results of previous studies suggest that physical fitness and motor skills are differently related to the different aspects of executive functioning (Marchetti et al., 2015; Niederer et al., 2011; also see Haapala, 2013), providing some support for this idea. Further examination of whether the different relations between physical fitness and motor skills with aspects of executive functioning can explain the specific relations between fitness, motor skills and academic achievement in the distinct domains is important for future research. A full mediation model including physical, cognitive, and academic measures could be used to examine this hypothesis. In addition to providing insight into the exact relations between physical, cognitive, and academic skills, this model will provide important suggestions for how improvements in fitness/motor skills can be beneficial for academic achievement, and how different types of physical activity can be helpful in that sense.

7.3.2 MECHANISMS UNDERLYING EFFECTS OF PHYSICAL ACTIVITY ON ACADEMIC ACHIEVEMENT

Following the hypothesis presented above, it was expected that effects of physical activity on academic achievement would depend on the type of physical activity involved. Therefore, the second aim of this dissertation was to examine the effects of two different types of physical activity interventions on academic achievement. The interventions were developed based on the two neurobiological mechanisms that have been brought forth to explain effects of physical activity on cognition and academic achievement. The first of these are physiological mechanisms, which state that aerobic physical activity results in changes in brain structure and functioning as a result of physiological changes in the brain (Alvarez-Bueno et al., 2017; Best, 2010; Donnelly et al., 2016). The second is a cognitive stimulation mechanism, in which it is argued that cognitively-engaging physical activity activates the same brain areas as those used during cognitive and academic tasks, thereby improving the efficiency with which these regions work (Crova et al., 2014; Pesce, 2012). As both mechanisms refer to underlying changes in the brain, the effects of the two interventions on brain activation were examined as well. By comparing the effects of two interventions on academic achievement and brain activation, the aim was to get a better understanding of *how* physical activity affects academic achievement.

In contrast to what was expected, the interventions did not improve children's achievement in reading, mathematics, or spelling, nor did they result in significant changes in brain activation. Some support was provided for the physiological and developmental mechanisms, as a higher volume of MVPA was found to bring about positive effects on academic achievement. It thus seems important to expose children to a high enough volume of MVPA in order to result in improved academic achievement. Especially in the cognitively-engaging intervention, the intensity of physical activity proved to be important, as children who were exposed to a higher volume of MVPA performed better in mathematics and spelling at the posttest. For the aerobic intervention, this improvement in performance for children who participated at a higher volume of MVPA was only found for mathematics. Based on this finding, it can be hypothesized that the two mechanisms by themselves, thus a focus on either intensity (aerobic) or type (cognitively-engaging) of physical activity, were not strong enough to bring about improved academic achievement. Probably, both the quantitative and qualitative aspects of physical activity are important to take into account when trying to improve academic achievement via physical activity. In line with this argumentation, a study by Schmidt and colleagues (2015) reported the strongest effects on cognition for aerobic physical activity that also contained cognitively-engaging exercises. Further examination of the effects of this type of physical activity on academic achievement thus seems promising.

Although the aim of the project was to tear apart the effects of different types of physical activity by implementing two different physical activity interventions, it should be noted that the interventions were not purely aerobic or purely cognitively-engaging. That is, the aerobic intervention also included cognitively-engaging aspects, for example when children had to work in teams, or when they engaged in dancing activities. Likewise, the cognitively-engaging intervention included aerobic aspects such as running and jumping. In practice, most types of physical activity include both aerobic and cognitively-engaging aspects, however, making it difficult to isolate the two (Schmidt, Jäger, Egger, Roebers, & Conzelmann, 2015). This underlines the importance of further examining physical activity that combines cognitive engagement with aerobic activities.

The non-significant intervention effects are contrasting positive results of studies that have examined effects of physically active learning on academic achievement, that is: being physically active while solving academic tasks (e.g.; Mullender-Wijnsma et al., 2016). Although these studies also examine effects of physical activity on academic achievement, they differ in the way they aim to bring about these effects, by integrating physical activity and learning instead of focusing on physical activity in itself. Further, they partly rely on a different theoretical framework, namely embodied cognition (Kontra, Goldin-Meadow, & Beilock, 2012). These differences provide an explanation for why positive effects of this type of interventions are found, whereas our interventions did not bring about significant changes in academic achievement.

7.3.3 EXPLORING THE EFFECTS OF PHYSICAL ACTIVITY ON THE BRAIN

In addition, by examining effects of physical activity on brain activation we aimed to reveal mechanisms underlying the effects of physical activity on academic achievement. However, this proved to be difficult, since no significant effects on academic achievement were found. Still, it is known from previous research that changes in the brain can precede behavioral effects (e.g. Ross & Tremblay, 2009; Tremblay, Kraus, & McGee, 1998). The non-existent behavioral effects on academic achievement did thus not necessarily rule out neuronal effects on brain activation.

Unfortunately, in line with the non-significant intervention effects on academic achievement, the interventions did not have significant effects on brain activation during a visuospatial working memory task. On the one hand, this seems to implicate that physical activity does not bring about changes in brain activation, meaning that the neurobiological framework as presented here might not be suitable to explain how physical activity affects academic achievement. On the other hand, an explanation for these non-significant effects can be found in the task that was used during brain imaging. No significant relations between physical fitness, motor skills, and task-related brain activation were found in Chapter 4, and characteristics such as age and gender were not related to brain activation patterns. This is a very surprising finding, as there are strong reasons to believe that such background characteristics are associated with visuospatial working memory related brain activation (e.g. Barriga-Paulino, Benjumea, Rodríguez-Martínez, & González, 2015; Schweinsburg, Nagel, & Tapert, 2005; Thomason et al., 2009; Zilles et al., 2016). Based on these results, it can be questioned whether the visuospatial working memory task that we used was sensitive enough to pick up intervention effects on brain activation. Before arguing that the neurobiological framework needs to be discarded as an explanation of the link between physical activity and academic achievement, it thus seems important for future research to also implement other methods to assess effects of physical activity on brain activation. This conclusion is substantiated by the fact that we found some indications of changes in brain activation patterns when comparing the three groups. Although we have to be cautious with drawing firm conclusions from these results, because of their instability, they suggest that the neurobiological framework should not immediately be discarded in future studies. Although the evidence provided here is not overwhelming, it seems that physical activity can have effects on children's brain activation, with different effects depending on the type of activity used.

7.3.4 INTRA-INDIVIDUAL VARIATION IN INTERVENTION EFFECTS

Interestingly, there seemed to be large variation between children in the intervention groups in posttest academic achievement and brain activation, suggesting that the intervention effects were different for individual children. One factor that seemed to influence intervention effectiveness was initial level of academic achievement. Lower-achieving children in reading at baseline performed better in reading after the cognitively-engaging intervention compared to children in the control group. It was already expected that lower-achieving children would benefit more from the interventions, because they have most room for improvement (Diamond, 2012; Diamond & Lee, 2011; Diamond & Ling, 2016). Following this line of reasoning, a similar effect could be expected for low achievers in mathematics and spelling however. It is therefore surprising that this effect was only found for lower-achieving children in reading. Possibly, it is not per se that lower achievers have more room for improvement, but rather that they benefit from physical activity in a different manner (Diamond & Lee, 2011). As was shown in Chapter 2, physical fitness was related to low academic achievement via different executive functions, depending on the domain of low performance. Although the relations were not compared for lower-achieving and higher-achieving children, it can be hypothesized that these relations differ for the two groups, thereby possibly also explaining why lower-achieving children benefit from physical activity interventions in a different manner. For future work, it would be interesting to examine whether cognitive functions such as executive functioning are differently targeted by physical activity interventions in lower-achieving compared to higher-achieving children, and whether that can explain the differential effects on academic achievement.

In previous research it has been argued that the way in which physical activity affects cognition and academic achievement is not only influenced by characteristics of physical activity, such as intensity, duration, or type, but also by characteristics of the individual involved (Pesce, 2012). This makes it likely that other factors than initial achievement are related to the large variation in intervention effects that was found here. Factors that are mentioned as moderators in the relation between physical activity and cognitive and academic performance are physical fitness level, health status (being overweight), psychosocial factors (Pesce, 2012), as well as gender, age, socioeconomic status, and cultural background (Tomporowski, Lambourne, & Okumura, 2011). Children might therefore respond differently to physical activity interventions, depending on their individual characteristics. This suggests that physical activity interventions should be individualized, by adapting the physical activity program to characteristics of the child (Gearin & Fien, 2016). Following Vygotsky's idea on the zone of proximal development (Vygotsky, 1978), physical activity interventions are possibly most effective when the games and exercises involved are offered at a level that is challenging children's cognitive and physical skills, but still doable under guidance of, or in collaboration with others. This implies that interventions should not be offered in the same way to an entire class, but rather in different forms to smaller groups of children with a similar skill level. Although this kind of differentiation is common good in academic classes, it is less often implemented in physical education. Physical education teachers indicate that they find differentiation important, but that they do not explicitly apply differentiation in their lessons, partly because they do not always know what works for which child (Spithoff, Naayer, Hartman, & Timmermans, 2017). More research into the individualized effects of physical activity therefore seems vital, as this will greatly increase our knowledge of *what works for whom*. This research might also give more insight into the mechanisms underlying effects of physical activity on academic achievement, thereby possibly also explaining why we did not find overall effects on academic achievement and brain activation.

7.3.5 EXAMINATION OF ADDITIONAL MECHANISMS

Although there is a strong rationale for examining changes in brain structure and functioning when trying to explain the effects of physical activity on academic achievement (see Donnelly et al., 2016), it can be questioned whether effects of physical activity on academic achievement can solely be explained by such a neurobiological framework. The inconclusive results of our study regarding the validity of the neurobiological framework suggest that it is important to also start exploring additional mechanisms that can explain the effects of physical activity on academic achievement. In line with this, more and more researchers underline the importance of taking into account different perspectives when trying to explain effects of physical activity on academic achievement (Bailey, 2016).

In explaining the effects of cognitively-engaging physical activity, a different mechanism already needs to be taking into account. It is expected that this type of physical activity not only results in neurobiological changes in the brain, but also in psychological changes via social interactions (Crova et al., 2014). This is an example of a psychosocial mechanism, in which it is hypothesized that physical activity affects academic achievement via psychosocial factors (Bailey, 2016; Lubans et al., 2016). In line with this mechanism, participation in physical activity results in amongst others higher levels of self-esteem, reduced anxiety (Biddle & Asare, 2011), and higher school engagement (Owen et al., 2016), which are consequently expected to be beneficial for children's academic achievement as well (Bailey, 2016; Lubans et al., 2016). Although the effects of cognitively-engaging physical activity on academic achievement were examined in this project, these mechanisms were not taken into account, as the focus was on explaining effects via neurobiological changes in the brain. Yet, especially in the scholastic setting, the psychosocial mechanisms can be expected to play a role, because it is one of the goals of education to contribute to children's psychosocial development by fulfilling their psychological and social needs.

Another mechanism that has been largely neglected in this domain of research is a behavioral mechanism, which hypothesizes that physical activity brings about positive effects on behaviors that are associated with mental and cognitive outcomes (Lubans et al., 2016). Increases in physical activity behavior are expected to result in amongst others higher sleep quality, and improved self-regulation and coping skills, which are consequently important predictors of academic achievement as well (Bailey, 2016; Lubans et al., 2016). For future research, it seems of vital importance to start examining these alternative hypotheses, besides the neurobiological framework, as they will help increasing our understanding of how physical activity can improve academic achievement.

7.3.6 PRACTICAL IMPLICATIONS

The findings from this project prove that spending more time on primary school physical education can result in improved academic achievement, depending on the type and amount of physical activity provided, and taking into account individual differences. In that sense, not the type or amount of physical activity per se, but rather a combination of the two seems to be important. The results of this dissertation suggest that the most beneficial effects are reached when children are engaged in cognitively-engaging physical activities at a moderate-to-vigorous intensity level. Further, lower-achieving children in reading seem to benefit from cognitively-engaging physical activity to a larger extent.

The results of this dissertation further suggest that the effects of physical activity interventions are different for individual children. One factor that was found to influence intervention effectiveness was children's initial achievement level. For educational practice, these results suggest that it is important to take into account individual differences between children when implementing physical activity programs. One way of achieving this is by adapting exercises to children's individual achievement level, i.e. differentiation.

Also, it was shown in this dissertation that it is feasible for primary schools to allocate more time to physical education than is currently done. Although the intended four lessons each week were not reached, on average children in the intervention groups were exposed to 3.2 lessons per week, which is substantially more than the two lessons per week they typically get. These are important findings, as many children do not meet the daily-recommended amount of physical activity, because they spend most of their time sedentary (Verloigne et al., 2012). This project shows that it is possible for primary schools to contribute to the daily amount of physical activity that children engage in.

In addition, it proved to be feasible to increase the intensity of physical education lessons. Previous research has shown that children in the Netherlands spend on average only 18 minutes in MVPA during physical education lessons (Singerland, Oomen, & Borghouts, 2011). This is partly the result of one of the main goals of physical education, namely learning motor skills, which is often done at a low intensity level. Still, 18 minutes per lesson is worryingly low, especially since being exposed to a higher volume of MVPA seems to bring about more beneficial effects on academic achievement (as was shown in this dissertation). Therefore, it seems important to increase the amount of time children are active in MVPA. In our study, children in the aerobic intervention spent on average 28% more time in MVPA compared to children in the control group, showing that it is feasible to increase the volume of MVPA in primary school physical education lessons.

7.4 CONCLUSION

Given the importance of physical activity for children's physical fitness, motor development, and health and wellbeing, children should be provided with many opportunities to be physically active. Schools present the perfect environment to provide these opportunities, as children spend most of their active time at school. Following the results presented in this dissertation, I agree with an argumentation that was recently made by Bailey (2016, p. 16):

> "… the ways in which schools are organized and presented to young people need to change. They are outdated and inadequate since they were designed (more than 100 years ago) with the vision of the child as passive and still, when it is now known that the child is an active and moving learner. Based on the evidence reported here, it can be plausibly claimed that schools need to offer a wide range of positive, attractive physical activities to all students."

Although physical activity thus can be seen as a promising method for enhancing children's academic achievement without focusing on the academic subject itself, the same argumentation can be put forward for other non-academic subjects such as music or arts (see Diamond & Ling, 2016). Yet, physical activity has additional benefits up and above the effects on cognition and academic achievement, as physical activity is also important for children's physical fitness, motor skills, and general health (Kohl & Cook, 2013; Morgan et al., 2013; Wu et al., 2017), as well as their social, emotional, and personality development (Bailey et al., 2009). Providing children with opportunities to be physical active during the school day can help in meeting the daily physical activity guidelines, thereby not only having positive effects on academic achievement, but also on children's physical, social, emotional, and personality development.

ADDENDUM

NEDERLANDSE SAMENVATTING

DOEL VAN HET PROEFSCHRIFT

Het hoofddoel van dit proefschrift was het onderzoeken van de effecten van twee typen fysieke activiteit, aerobe en cognitief-uitdagende, op schoolprestaties en hersenfuncties van 8-tot-10-jarige basisschoolleerlingen. Als een eerste stap zijn de relaties tussen fysieke, cognitieve, en academische vaardigheden onderzocht, evenals de relaties tussen fysieke vaardigheden en hersenfuncties. In deze studies is gekeken naar: 1) de mediërende rol van executieve functies in de relatie tussen fysieke fitheid en lage schoolprestaties; 2) de differentiële relaties van fysieke fitheid en motorische vaardigheden met schoolprestaties in lezen, rekenen en spelling; en 3) de relaties van fitheid en motorische vaardigheden met hersenfuncties tijdens een visueel werkgeheugen taak, gemeten met functionele hersenscans.

De resultaten van deze studies zijn vervolgens als leidraad gebruikt voor het tweede deel van dit proefschrift, waarin gekeken is naar de effecten van twee fysieke interventies op schoolprestaties: een interventie gericht op aerobe fysieke activiteit en een interventie gericht op cognitief-uitdagende fysieke activiteit. De aerobe interventie richtte zich op het verbeteren van de fitheid en conditie van kinderen door het aanbieden van spellen en oefeningen op een matig-tot-intensief intensiteitsniveau. De cognitief-uitdagende interventie had als doel het stimuleren van de motorische en cognitieve vaardigheden van leerlingen door middel van oefeningen met complexe bewegingen, of spellen met lastige en snel veranderende regels. Daarnaast is in het tweede deel van dit proefschrift gekeken naar de effecten van de twee interventies op hersenfuncties, om zo te achterhalen hoe fysieke activiteit veranderingen in schoolprestaties teweegbrengt.

SAMENVATTING VAN DE BELANGRIJKSTE BEVINDINGEN

In hoofdstuk 2 is gekeken naar de mediërende rol van executieve functies in de relatie tussen fysieke fitheid en lage schoolprestaties in rekenen en spelling. Executieve functies zijn cognitieve functies die belangrijk zijn voor doelgericht gedrag. Er wordt vaak onderscheid gemaakt tussen drie executieve functies: inhibitie (het vermogen om irrelevante prikkels te onderdrukken), verbaal en visueel werkgeheugen (de capaciteit om tijdelijk verbale en visuele informatie op te slaan en deze vervolgens te bewerken), en shifting (het vermogen om snel en flexibel tussen verschillende taken te wisselen). Mediatie betekent dat een relatie indirect verloopt. In dit geval was de verwachting was dat fysieke fitheid voorspellend zou zijn voor executief functioneren, en dat executief functioneren vervolgens voorspellend zou zijn voor lage schoolprestaties. Resultaten van deze studie lieten zien dat fysieke fitheid en executieve functies geen onafhankelijke voorspellers waren van lage schoolprestaties, maar dat executieve functies significante mediatoren waren in de relatie tussen fysieke fitheid en lage schoolprestaties. Dit betekent dat kinderen met een lagere fysieke fitheid, minder goed ontwikkelde executieve functies hadden, wat vervolgens voorspellend was voor lage schoolprestaties. De mediërende relatie was specifiek voor rekenen en spelling. Voor het domein van rekenen medieerden verbaal werkgeheugen en visueel werkgeheugen de relatie tussen fysieke fitheid en lage schoolprestaties, terwijl deze relatie voor spelling alleen gemedieerd werd door verbaal werkgeheugen.

In hoofdstuk 3 zijn de specifieke relaties tussen fysieke fitheid en motorische vaardigheden en schoolprestaties in de domeinen van begrijpend lezen, rekenen en spelling onderzocht. Motorische vaardigheden bleken een significante voorspeller te zijn voor gemiddelde schoolprestaties, terwijl fysieke fitheid dat niet was. Echter, wanneer schoolprestaties gesplitst werden in de losse domeinen van begrijpend lezen, rekenen, en spelling, bleek dat de relaties met fysieke fitheid en motorische vaardigheden specifiek waren voor de verschillende domeinen. Motorische vaardigheden waren significante voorspellers voor prestaties in rekenen en spelling, terwijl fysieke fitheid een significante voorspeller was voor prestaties in rekenen en begrijpend lezen.

In hoofdstuk 4 wordt het patroon van hersenactiviteit gedurende een taak voor visueel werkgeheugen beschreven, en de relaties van dit patroon met fysieke fitheid en motorische vaardigheden. Hersenactiviteit is gemeten door middel van functionele hersenscans (functional magnetic resonance imaging; fMRI), waarmee te zien is welke hersengebieden actief worden tijdens een bepaalde taak, in dit geval een taak voor visueel werkgeheugen. fMRI brengt de hoeveelheid zuurstofrijk bloed in beeld. Doordat het uitvoeren van een taak leidt tot meer doorbloeding in bepaalde hersengebieden, neemt de hoeveelheid zuurstofrijk bloed in dat hersengebied toe, wat vervolgens zichtbaar is op functionele scans. Het uitvoeren van de visueel werkgeheugen taak leidde tot meer hersenactiviteit in de gyrus angularis (rechter hemisfeer) en het bovenste deel van de pariëtale cortex (bilateraal, dus aan beide kanten van het brein), samengaand met minder activatie (deactivatie) in het onderste en middelste deel van de temporale gyrus (bilateraal). Dit patroon van activatie komt grotendeels overeen met wat er in eerdere studies die dezelfde taak gebruikten gevonden is. Tegen de verwachting in waren fysieke fitheid en motorische vaardigheden niet gerelateerd aan het patroon van hersenactiviteit tijdens de visueel werkgeheugen taak, althans, wanneer er geen manipulatie van deze fysieke vaardigheden plaatsvond.

De effecten van de twee fysieke interventieprogramma's, een aerobe interventie en een cognitief-uitdagende interventie, op schoolprestaties zijn beschreven in hoofdstuk 5. Beide interventies werden voor 14 weken geïmplementeerd in het bewegingsonderwijs. Leerlingen uit de groepen vijf en zes van 22 scholen kregen vier interventielessen per week aangeboden door een vakleerkracht aangesteld voor het geven van de interventieprogramma's. Leerlingen in de controlegroepen volgden ondertussen hun reguliere gymprogramma van twee lessen per week, gegeven door hun eigen gymleerkracht. De interventies hadden geen significant effect op schoolprestaties in begrijpend lezen, rekenen en spelling. De hoeveelheid matig-tot-intensieve activiteit bleek belangrijk te zijn. Leerlingen die gedurende de interventieprogramma's meer hadden meegedaan op een matig-tot-intensief intensiteitsniveau, scoorden tijdens de nameting hoger op rekenen. Voor spelling werd dit effect ook gevonden, maar dan alleen voor leerlingen in de cognitief-uitdagende interventie. Voor lezen kon dit effect niet aangetoond worden. Daarnaast werd gekeken of de interventies verschillende effecten hadden afhankelijk van de schoolprestaties van leerlingen voorafgaand aan de interventies. Hieruit bleek dat kinderen die lager scoorden op lezen op de voormeting, beter scoorden op lezen tijdens de nameting wanneer ze hadden deelgenomen aan de cognitief-uitdagende interventie, dan wanneer ze in de controlegroep zaten. Dit laat zien dat de cognitief-uitdagende interventie positieve effecten heeft gehad voor lager presterende leerlingen op lezen. Dit effect werd niet gevonden voor rekenen of spelling.

In het laatste hoofdstuk worden de effecten van de twee interventieprogramma's op hersenactiviteit gedurende een taak voor visueel werkgeheugen beschreven. Hoewel er in Hoofdstuk 4 geen relaties tussen fitheid, motoriek en hersenactiviteit gevonden werden, was de verwachting dat manipulatie van deze fysieke competenties wel effecten teweeg zou kunnen brengen op hersenactiviteit. Hiermee werd beoogd het mechanisme onderliggend aan de effecten van fysieke activiteit op schoolprestaties te achterhalen. Tegen de verwachting in leidden de twee interventies niet tot significante veranderingen in hersenactiviteit. In aanvullende analyses is vervolgens gekeken of er patronen van hersenactiviteit waren op basis waarvan er onderscheid gemaakt kon worden tussen de interventiegroepen en de controlegroep. Uit deze analyses bleek dat activiteit in bepaalde hersengebieden, met name in de frontale, occipitale, en pariëtale gebieden, inderdaad onderscheid kon maken tussen kinderen uit de verschillende groepen, waarbij verschillende activatiepatronen gevonden werden voor kinderen uit de twee interventiegroepen. Er was echter grote variëteit tussen kinderen in de drie groepen, waardoor de resultaten niet stabiel genoeg waren om definitieve conclusies te trekken. Het lijkt er dus op dat fysieke activiteit effecten teweeg kan brengen op hersenfuncties, waarbij het effect afhankelijk is van het type fysieke activiteit, hoewel het bewijs niet overweldigend is.

CONCLUSIE

Concluderend bevestigt dit onderzoek de relaties tussen fitheid, motorische vaardigheden, executieve functies en schoolprestaties bij basisschoolleerlingen, die in eerdere onderzoeken ook aangetoond zijn. Bovendien blijkt uit dit proefschrift dat deze relaties specifiek zijn. Afhankelijk van het academisch domein dat onderzocht wordt, blijken er verschillende relaties te zijn tussen fysieke, cognitieve en schoolse vaardigheden. Daarnaast kan op basis van de resultaten van dit onderzoek gesteld worden dat fysieke interventies positieve effecten teweeg kunnen brengen op schoolprestaties, met name wanneer matig-tot-intensieve activiteiten gecombineerd worden met cognitieve uitdaging. Praktische implicaties hiervan zijn dat het aanbieden van meer bewegingsonderwijs positief kan zijn voor schoolprestaties, zolang het intensiteitsniveau hoog genoeg is, en zolang er sprake is van cognitieve uitdaging. De exacte mechanismen onderliggend aan de gevonden effecten blijven echter onduidelijk, aangezien er in dit onderzoek geen eenduidige effecten op hersenactiviteit gevonden werden. Voor toekomstig onderzoek lijkt het van belang om naast de effecten op hersenactiviteit ook te kijken naar andere mechanismen die de effecten van fysieke activiteit op schoolprestaties kunnen verklaren, zoals de effecten op slaapkwaliteit en zelf-regulatieve vaardigheden van kinderen, welke verwacht worden ook positief bij te dragen aan schoolprestaties.

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APPENDICES

APPENDIX 1: CORRELATION MATRICES (CHAPTER 2)

TABLE 1.1. Bivariate correlations between variables included in the models Mplus

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Mathematics	-												
2. Spelling	.23***	-											
3. Inhibition	.07	-.02	-										
4. VWM	.20***	.14**	.06	-									
5. VSWM	.36***	.05	.06	.19***	-								
Shifting													
6. MWCST efficiency	.17***	.06	.01	.22***	.23***	-							
7. MWCST pers. errors	.12**	.08	-.08	.19***	.17***	.44***	-						
Fitness													
8. SBJ	.07	-.04	.08	.13**	.11*	.12*	.16***	-					
9. Plate-tapping	-.09	-.03	-.21***	-.12*	-.17***	-.13**	-.04	-.27***	-				
10. 10x5m SR	-.19***	-.01	-.09	-.07	-.18***	-.16***	-.18***	-.52***	.35***	-			
11. 20m SR	.11*	.03	.04	.08	.12*	.17***	.14**	.35***	-.17***	-.47***	-		
12. Gender	.08	-.12**	.03	-.01	.14**	-.03	.08	.20***	-.03	-.21***	.25***	-	
13. Age	-.01	-.14**	.06	.07	.15***	.14**	.14**	.28***	-.31***	-.20***	.02	.04	-

Note* < .05 ** < .01 *** < .001
VWM = Verbal working memory, VSWM = Visuospatial working memory, SBJ = Standing broad jump, SR = Shuttle run

TABLE 1.2. Correlations between latent and manifest variables included in the SEM-models.

	1.	2.	3.	4.	5.	6.	7.
1. Fitness	-						
2. Inhibition	.13	-					
3. VWM	.15*	.08	-				
4. VSWM	.29***	.09	.30***	-S			
5. Shifting	.33***	-.05	.37***	.39***	-		
6. Mathematics	.20*	.08	.23***	.48***	.21***	-	
7. Spelling	-.04	-.04	.12*	-.05	.06	.00	-

Note: * < .05 ** < .01 *** < .001
VWM = verbal working memory, VSWM = visuospatial working memory

APPENDIX 2: FULL STRUCTURAL EQUATION MODEL PRESENTING ALL INCLUDED PATHS (CHAPTER 2)

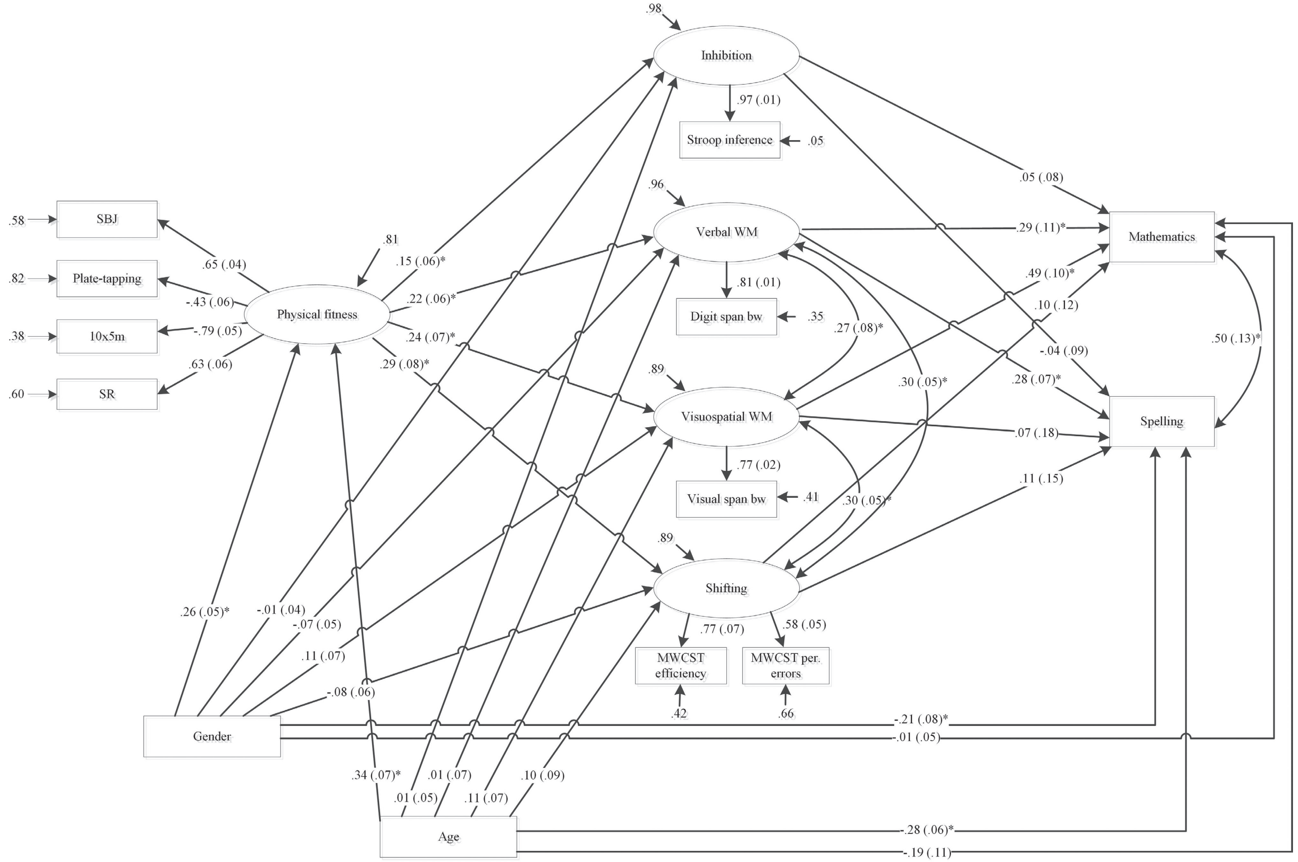

FIGURE 2.1. Full SEM-model including non-significant paths, factor loadings, error terms and covariances between physical fitness, executive functioning and academic achievement, controlling for gender and age. Standardized path coefficients (ß) and associated standard errors are displayed in the figure. Note: asterisks indicate significant paths between variables.

APPENDIX 3: ANALYSIS WITH CONTINUOUS OUTCOME VARIABLES (CHAPTER 2)

A model was fitted with continuous outcome variables for mathematics and spelling achievement. Based on modification indices, a covariance between age and plate tapping was added to improve model fit. This resulted in a model which fitted the data well (χ^2 (39) = 95.38, $p < .001$, RMSEA =.055, CFI = .95). In total, 51.6% of the variance in mathematics achievement ($p < .001$) and 34.4% of the variance in spelling achievement ($p < .001$) was explained by this model including direct and indirect relations between physical fitness, executive functioning and academic achievement.

MATHEMATICS

Verbal working memory (ß = .17, $p = .008$, 95% CI: .04 to .29), visuospatial working memory (ß = .39, $p < .001$, 95% CI: .27 to .51) and shifting (ß = .14, $p = .001$, 95% CI: .06 to .23) were significant predictors of mathematics achievement. The total effect of physical fitness to mathematics achievement was significant (ß = .28, $p < .001$, 95% CI: .20 to .36). Physical fitness was both directly (ß = .13, $p = .017$, 95% CI: .02 to .23) and indirectly (ß = .15, $p < .001$, 95% CI: .08 to .22) related to mathematics achievement. The total indirect effect from physical fitness to mathematics achievement accounted for a significant 54.9% of the total effect. The direct effect accounted for a significant 45.1% of the total effect. The indirect paths between physical fitness and mathematics achievement via visuospatial working memory (ß = .08, $p = .011$, 95% CI: .02 to .15) and via shifting (ß = .04, $p = .003$, 95% CI: .01 to .07) were found to be significant. The indirect path via verbal working memory just failed to reach significance (ß = .03, $p = .061$, 95% CI: -.001 to .06).

SPELLING

Verbal working memory (ß = .33, $p < .001$, 95% CI: .22 to .44) and shifting (ß = .14, $p = .003$, 95% CI: .05 to .24) were significant predictors of spelling achievement. The total effect of physical fitness to spelling achievement was significant (ß = .26, $p < .001$, 95% CI: .07 to .35). Physical fitness was only indirectly (ß = .11, $p = .001$, 95% CI: .04 to .17) related to spelling achievement. The total indirect effect from physical fitness to spelling achievement accounted for a significant 50.9% of the total effect. The direct effect accounted for 49.1% of the total effect, which was not significant (ß = .10, $p = .12$, 95% CI: -.03 to .24). The indirect paths between physical fitness and spelling achievement via verbal working memory (ß = .05, $p = .015$, 95% CI: .01 to .10) and via shifting (ß = .04, $p = .012$, 95% CI: .01 to .07) were found to be significant.

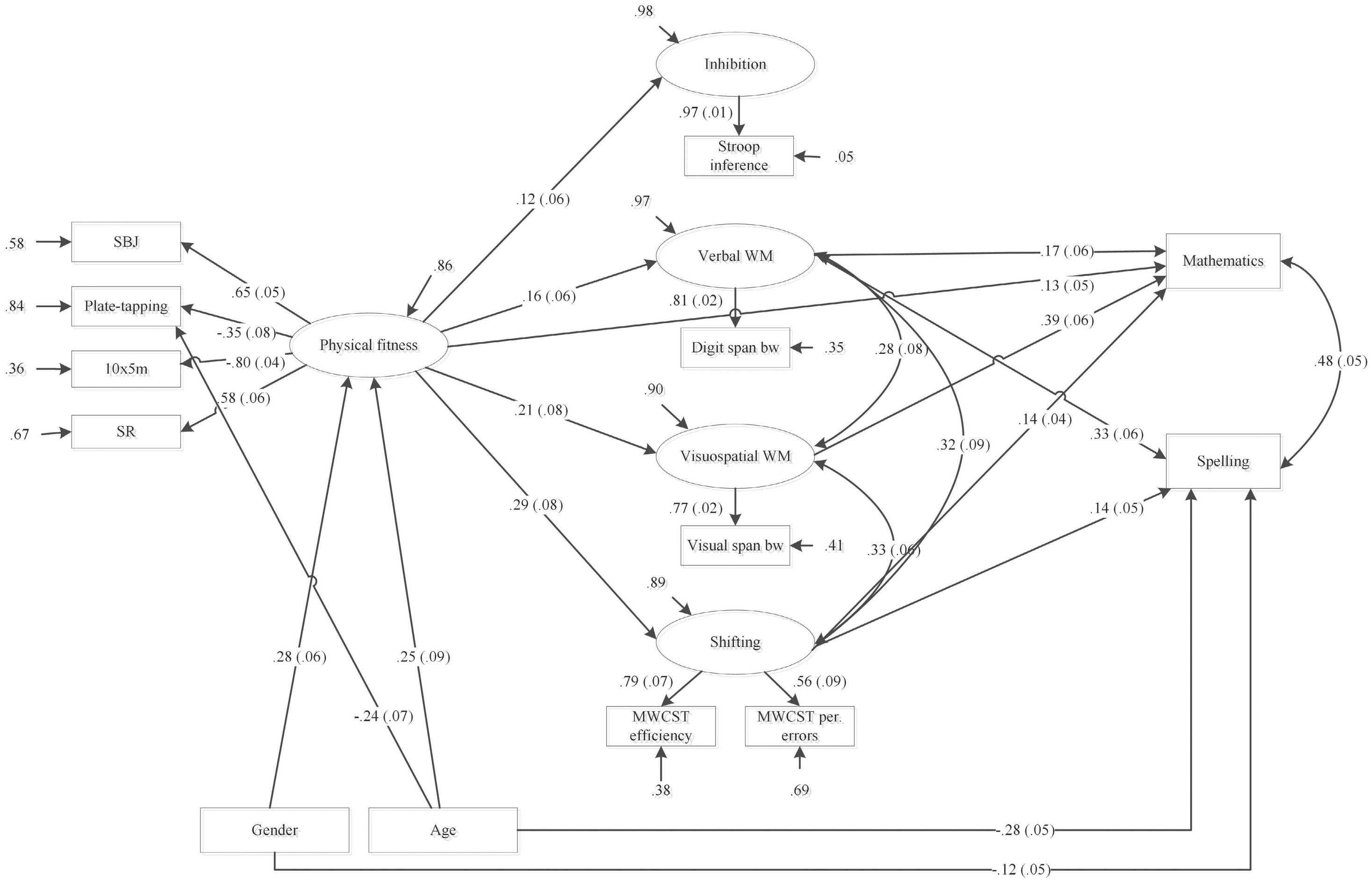

FIGURE 3.1. *Significant paths between physical fitness, executive functioning and achievement (continuous) in mathematics and spelling, controlling for gender and age. Standardized path coefficients (ß) and associated standard errors are displayed in the figure.*

CONCLUSIONS

In line with the results of our model with dichotomous outcome variables for mathematics and spelling achievement, we found significant direct and indirect relations with/via verbal working memory in both domains, and visuospatial working memory specifically in the domain of mathematics. Surprisingly, we also found significant direct and indirect relations with/via shifting. This is contrary to what we found in our model with dichotomous outcome variables, as there shifting was not a significant predictor of low academic achievement or mediator between physical fitness and academic achievement. It thus seems that shifting is important for academic achievement, but is not specifically predictive of low academic achievement. That is: low academic achievers are not necessarily characterized by low shifting ability. This conclusion is in line with previous research in Dutch students with learning difficulties, where students with learning difficulties did not show impaired shifting performance compared to their peers without cognitive difficulties (van der Sluis, de Jong, & van der Leij, 2004). Alternatively, the non-significant relation between shifting and low academic achievement when using a dichotomous outcome variable could be attributed to the loss of statistical power when using a dichotomous instead of a continuous outcome variable.

APPENDIX 4: FULL STRUCTURAL EQUATION MODEL PRESENTING ALL INCLUDED PATHS (CHAPTER 3)

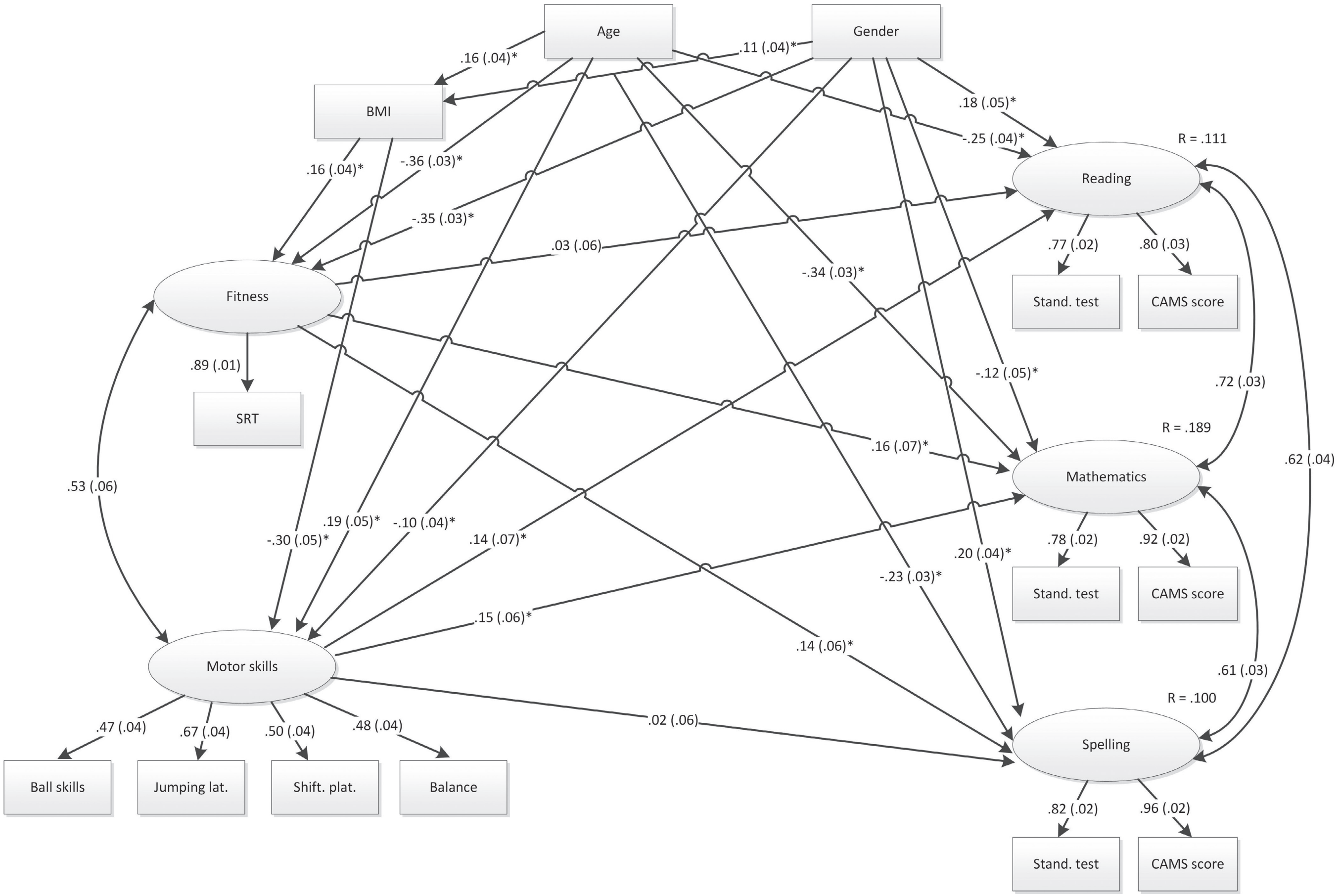

FIGURE 4.1. Full structural equation model presenting all included paths between latent variables. Notes: Asterisks indicate significant paths between variables. BMI, Body Mass Index; SRT, Shuttle Run Test; lat., laterally; shift. plat., shifting platforms; Stand., standardized; CAMS, Child Academic Monitoring System.

APPENDIX 5: INCLUSION PROTOCOL (CHAPTER 4)

This table shows the number of children per grade/gender/scan site that were planned to be scanned, that were actually scanned and that were used for analyses.

TABLE 5.1. Number of children planned, scanned, and analyzed.

Boys	*Grade 3*	*Grade 4*	*Total*
Planned	23	22	45
Scanned	24	21	45
Analyzed	20	19	39
Amsterdam planned	12	10	22
Amsterdam scanned	13	10	23
Amsterdam analyzed	11	10	21
Groningen planned	11	12	23
Groningen scanned	11	11	22
Groningen analyzed	9	9	18
Girls			
Planned	22	23	45
Scanned	22	25	47
Analyzed	18	23	41
Amsterdam planned	12	11	23
Amsterdam scanned	12	12	24
Amsterdam analyzed	11	12	23
Groningen planned	10	12	22
Groningen scanned	10	13	23
Groningen analyzed	7	11	18
Total			
Planned	45	45	90
Scanned	46	46	92
Analyzed	38	42	80
Amsterdam planned	24	21	45
Amsterdam scanned	25	22	47
Amsterdam analyzed	22	22	44
Groningen planned	21	24	45
Groningen scanned	21	24	45
Groningen analyzed	16	20	36

APPENDIX 6: RESULTS OF THE CONTRIBUTION OF THE COVARIATES TO VSWM-RELATED BRAIN ACTIVATION (CHAPTER 4)

Age, gender and SES did not contribute significantly to VSWM-related brain activation ($p > 0.05$). However, there was a significant difference between brain activation of children scanned in Amsterdam and those who were scanned in Groningen (Figure 6.1), located bilateral in superior parietal gyrus and the anterior prefrontal gyrus, bilateral in the premotor and supplementary motor cortex, and left in the angular gyrus and the inferior frontal gyrus. Scan site was included as covariate in all analyses.

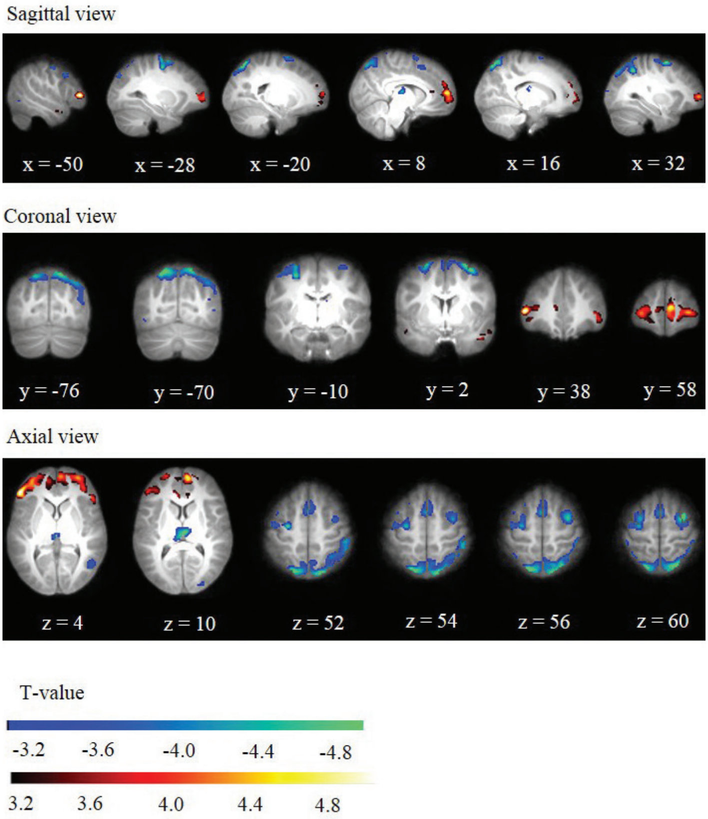

FIGURE 6.1. Difference in brain activation between children scanned in Amsterdam and in Groningen. Axial (upper), coronal (middle) and sagittal view (lower). Threshold is set at p < 0.001 (uncorrected). Warm colours indicate activation in children scanned in Amsterdam as compared to children scanned in Groningen. Cool colours indicate deactivation in children scanned in Amsterdam as compared to children scanned in Groningen. MNI coordinates (x, y, and z) represent the location of the maximum intensity voxel.

TABLE 6.1. Significant clusters of brain activation associated with scan site.

				MNI coordinates[a]		
Cluster	Anatomical label(s)	Hemisphere	N voxels	X	Y	Z
1	Superior parietal gyrus, angular gyrus[a]	Right	739	-20	-70	56
2	Superior parietal gyrus[b]	Left	1907	16	-76	54
3	Premotor cortex, supplementary motor cortex[b]	Right	725	32	2	60
4	Premotor cortex, supplementary motor cortex[b]	Left	601	-28	-10	52
5	Inferior frontal gyrus and anterior frontal gyrus	Left	829	-50	38	4
6	Anterior prefrontal gyrus	Right	1429	8	58	10

Note: Activation for the working memory contrast that survived the cluster level significance of $p < 0.05$, family wise error (FWE) corrected, initial threshold $p < 0.001$. N voxels: number of voxels involved in the significant cluster (total brain volume consisted of 153138 voxels). [a.] Brain coordinates defined by the Montreal Neurological Institute (MNI), based on which the location of (de)activated clusters of voxels can be identified. MNI coordinates represent the location of the maximum intensity voxel. [b.] Brain areas indicating deactivation in children scanned in Amsterdam as compared to children scanned in Groningen.

APPENDIX 7: INCLUSION FLOWCHART (CHAPTER 5)

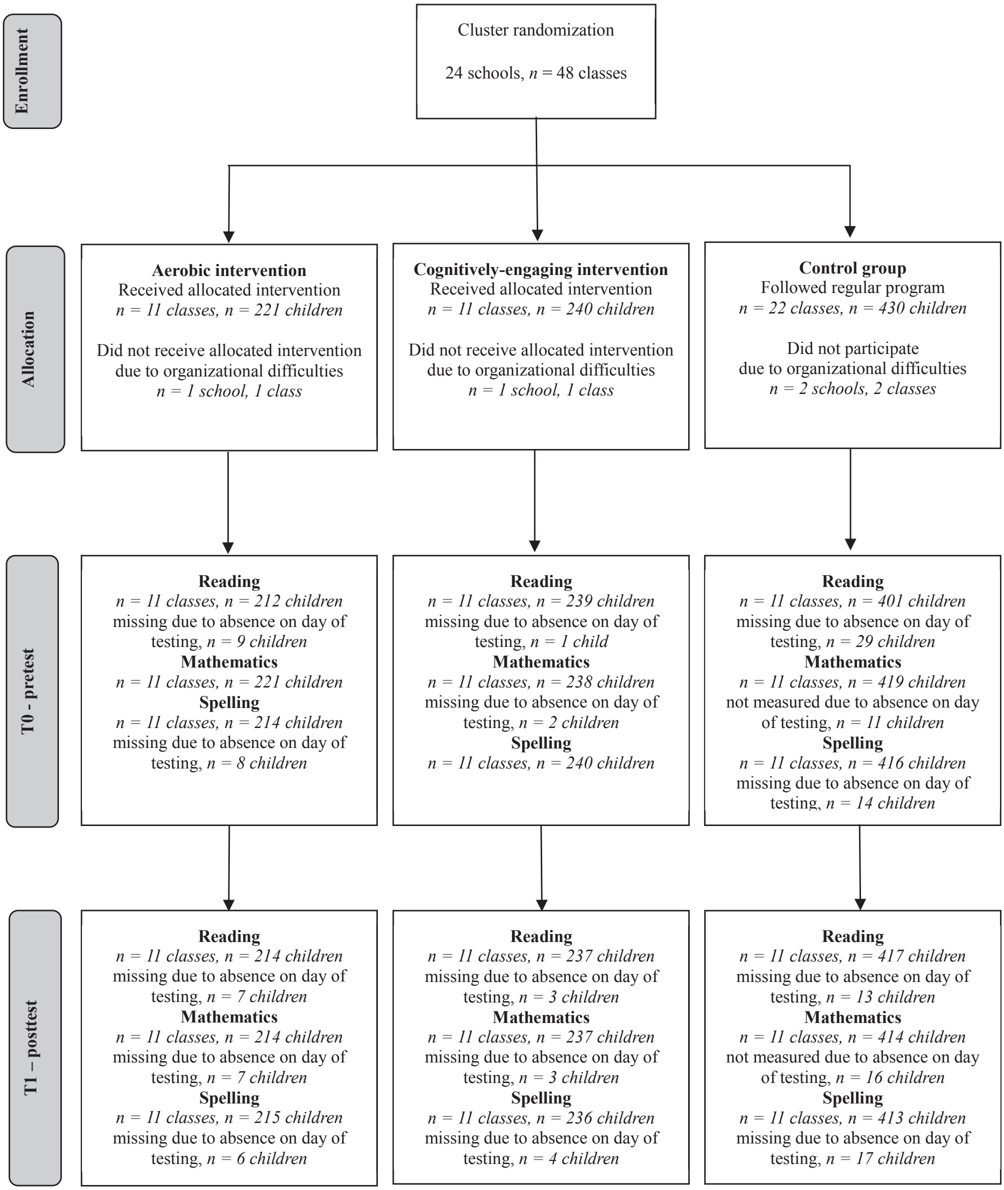

FIGURE 7.1. Flow chart with the number of participating classes and children in each stage of the study. Note: by using Full-Information Maximum Likelihood (FIML) estimation in Mplus, all cases could be included in the analyses.

APPENDIX 8: CALCULATION OF MVPA (CHAPTER 5)

In all three groups, MVPA was measured during two physical education lessons using accelerometers (ActiGraph GT3x+, Pensacola, FL, USA). The accelerometer was attached to the child's right hip using an elastic belt. Accelerations in three directions were measured with a frequency of 100 Hz. Data analyses were done in the software ActiLife (v6.8.2). Only data of the vertical axis were used for analysis. An epoch length of 1 second was chosen (Trost, Loprinzi, Moore, & Pfeiffer, 2011). The cut-off points used to determine the number of counts per minute were as follows: moderate: 2296 – 4011 counts/min, vigorous: > 4012 counts/min (Evenson, Catellier, Gill, Ondrak, & McMurray, 2008). As a measure of MVPA, time spent at a moderate and at a vigorous intensity level (in minutes) was summed and averaged over the two lessons.

Intensity of the physical education lessons differed between the three groups (F (2, 806) = 45.81, $p < .001$), with a higher intensity in the aerobic intervention (M = 12.36, SD = 3.08) than in the cognitively-engaging intervention (M = 9.29, SD = 2.47, $p < .001$) and the control condition (M = 10.65, SD = 3.70, $p < .001$). The intensity of the cognitively-engaging intervention was lower than that of the control group ($p < .001$).

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Trost, S. G., Loprinzi, P. D., Moore, R., & Pfeiffer, K. A. (2011). Comparison of accelerometer cut points for predicting activity intensity in youth. *Medicine and Science in Sports and Exercise*, *43*(7), 1360-1368. doi: 10.1080/02640410802334196

APPENDIX 9: ANALYSIS ON MVPA AND BASELINE ACADEMIC ACHIEVEMENT (CHAPTER 5)

9.1. RESULTS OF THE MODELS EXAMINING THE RELATION BETWEEN MVPA AND INTERVENTION EFFECTS ON ACADEMIC ACHIEVEMENT

A model with an added relation between volume of MVPA and academic achievement posttest scores resulted in an adequate fit (χ (21) = 55.49, RMSEA = .06, CFI = .98, SRMR = .07). Volume of MVPA was positively related to posttest mathematics achievement (β = .09 (.04), p = .02, 95% CI [.02 to .17]). This relation was not found for reading (β = -.04 (.05), p = .51, 95% CI [-.14 to .07]) nor for spelling (β = .002 (.04), p = .96, 95% CI [-.07 to .07]).

In a follow-up analysis, an interaction term between volume of MVPA and condition was added. This model proved to have an adequate fit to the data (χ (27) = 88.78, RMSEA = .08, CFI = .96, SRMR = .06). Although the RMSEA was above the predetermined cut-off value, we still decided to use the model, as all other values were acceptable. The interaction between volume of MVPA and condition was significantly related to posttest achievement in spelling (β = .24 (0.10), p = .01, 95% CI [.05 to .43]). No relation was found with posttest achievement in reading (β = .05 (.17), p = .78, 95% CI [-.29 to .38]) or mathematics (β = .07 (.13), p = .60, 95% CI [-.19 to .33]), indicating that volume of MVPA was not differently related to posttest achievement in reading or mathematics for the two interventions.

9.2. RESULTS OF THE MODEL EXAMINING INTERACTIONS BETWEEN CHILDREN'S INITIAL LEVEL OF ACHIEVEMENT AND INTERVENTION

The third aim of this study was to examine whether children's prior level of achievement was related to the intervention effects. The model with an added interaction between pretest scores and the dummy variables for condition had an adequate fit to the data (χ (62) = 236.72, RMSEA = .06, CFI = .95, SRMR = .09).

Children with lower performance in reading at baseline performed better in reading at the posttest in the cognitively-engaging intervention group than in the control group (β = -.06 (0.03), p = .03, 95% CI [-.11 to -.01]), see Figure 5.3. No significant relation was found for the interaction between the dummy variable contrasting the cognitively-engaging intervention group and the control group and baseline mathematics performance (β = -.03 (.04), p = .37, 95% CI [-.11 to .04]), or baseline spelling performance (β = .07 (.04), p = .06, 95% CI [-.01 to .14]).

The interaction term between baseline performance and the dummy variable contrasting the aerobic intervention and the control group was not significant for reading (β = -.01 (.03), p = .75, 95% CI -.07 to .05]), mathematics (β = -.01

(.04), *p* = .82, 95% CI [-.09 to .07]), or spelling (β = .03 (.03), *p* = .37, 95% CI [-.03 to .10]). The effectiveness of the aerobic intervention did not differ depending on baseline academic performance.

APPENDIX 10: INCLUSION PROTOCOL (CHAPTER 6)

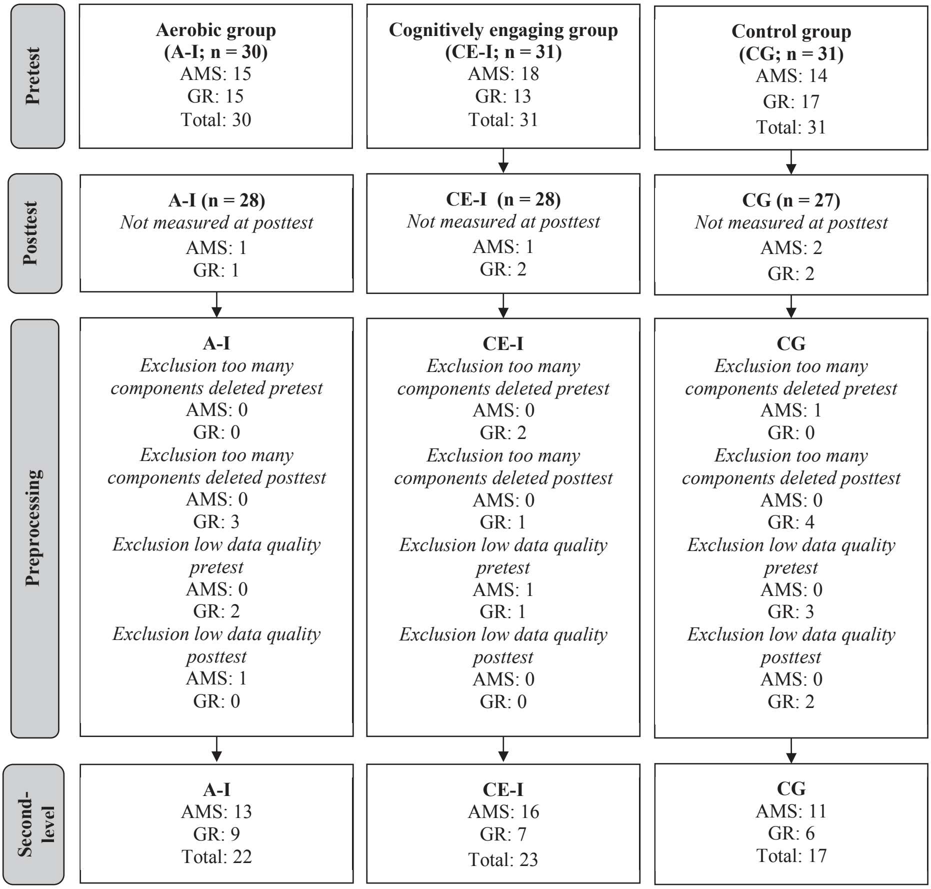


FIGURE 10.1. Flowchart of the number of included children in the control group, aerobic intervention group and cognitively-engaging intervention group at each stage of the study, in total and separated per study site.

Note. AMS = Amsterdam; GR = Groningen; A-I = aerobic intervention group; CE-I = cognitively-engaging intervention group; CG = control group

TABLE 10.1. Inclusion table showing the closely matched inclusion protocol (i.e. number of children per grade, gender, and scan site) that were planned to be scanned, that were actually scanned and that were used in the final analyses.

	Control group			Aerobic group			Cognitively-engaging group			Total		
	Grade 3	Grade 4	Total	Grade 3	Grade 4	Total	Grade 3	Grade 4	Total	Grade 3	Grade 4	Total
Boys planned	8	7	15	8	7	15	7	8	15	23	22	45
Boys scanned	5	7	12	7	7	14	8	7	15	20	21	41
Boys analyzed	2	5	7	7	4	11	6	6	12	15	15	30
Boys AMS planned	4	3	7	4	3	7	4	4	8	12	10	22
Boys AMS scanned	2	4	6	6	3	9	4	4	8	12	11	23
Boys AMS analyzed	1	3	4	6	2	8	4	4	8	11	9	20
Boys GR planned	4	4	8	4	4	8	3	4	7	11	12	23
Boys GR scanned	3	3	6	1	4	5	4	3	7	8	10	18
Boys GR analyzed	1	2	3	1	2	3	2	2	4	4	6	10
Girls planned	7	8	15	7	8	15	8	7	15	22	23	45
Girls scanned	6	9	15	7	8	15	7	6	13	20	23	43
Girls analyzed	3	7	10	5	6	11	5	6	11	13	19	32
Girls AMS planned	4	4	8	4	4	8	4	3	7	12	11	23
Girls AMS scanned	2	5	7	2	4	6	6	3	9	10	12	22
Girls AMS analyzed	2	5	7	2	3	5	5	3	8	9	11	20
Girls GR planned	3	4	7	3	4	7	4	4	8	10	12	22
Girls GR scanned	4	5	9	5	4	9	1	3	4	10	12	22
Girls GR analyzed	1	2	3	3	3	6	0	3	3	4	8	12

TABLE 10.1. Continued.

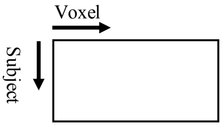
	Control group			Aerobic group			Cognitively-engaging group			Total		
	Grade 3	Grade 4	Total	Grade 3	Grade 4	Total	Grade 3	Grade 4	Total	Grade 3	Grade 4	Total
Total planned	15	15	30	15	15	30	15	15	30	45	45	90
Total scanned	11	16	28	14	15	29	15	13	28	40	44	85
Total analyzed	5	12	17	12	10	22	11	13	23	28	34	62
Total AMS planned	8	7	15	8	7	15	8	7	15	24	21	45
Total AMS scanned	4	9	13	8	7	15	10	7	17	22	23	45
Total AMS analyzed	3	8	11	8	5	13	9	7	16	20	20	40
Total GR planned	7	8	15	7	8	15	7	8	15	21	24	45
Total GR scanned	7	8	15	6	8	14	5	6	11	18	22	40
Total GR analyzed	2	4	6	4	5	9	2	5	7	8	14	22

Note. AMS = Amsterdam; GR = Groningen

APPENDIX 11: DESCRIPTION OF THE SSM/PCA AND LOOCV ANALYSIS METHOD (CHAPTER 6)

The SSM/PCA method was implemented in-house in MATLAB. The preprocessed difference maps — representing changes in activation between pretest and posttest — were loaded into a two-dimensional data matrix Y, in which rows represented subjects (both reference and intervention group), and columns represented voxels **(1)**.

$Y =$



Y (1)

Following, a binary mask was created to define the gray matter brain areas to which to restrict the analysis. Segmentation was applied to each subject's structural T1 scan (for both pretest and posttest) using the default Tissue Probability Map in the segment function in SPM12. Individual subject's gray matter segments (for both pretest and posttest) were combined to create a group, binary, gray matter mask.

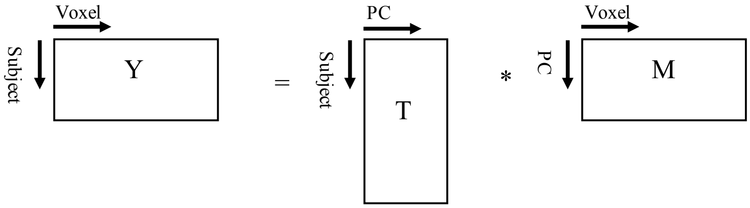
A centered version of the subject by voxel matrix was created by subtracting the control group mean profile vector (GMP; representing the mean regional activity in one voxel across all control group subjects) from each subject's difference map (y_i) **(2)**.

$$y_i' = y_i - \mathrm{GMP}(Y)_{\text{control group}} \qquad (2)$$

where i represents an index for the subject

This way, activity offset was removed for each voxel; only residual values were retained. That is, positive values indicate more activation (or less deactivation) than the mean activity of the reference group and vice versa for negative values. The resulting matrix Y' (subject by voxel) represented regional residual activity (only in gray matter voxels).

By applying a PCA, Y' was rewritten as a multiplication of two matrices:



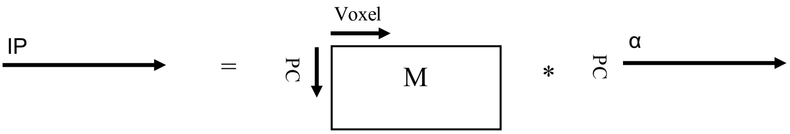
(3)

In this multiplication, T represents the extent to which each PC fitted a subject's activity pattern (subject by PC). M represents the contribution (weight) of each voxel to each PC (component by voxel). The PCAs of the two groups together was required to account for (at least) 50% of the variance, while retaining as few PCs as possible.

STEPWISE FORWARD LOGISTIC REGRESSION

Subject scores per PC were entered into a stepwise forward logistic regression model, with group (intervention, reference) as the dependent variable, and the subject scores for individual PCs as the independent variables. PCs were sorted based on their ability to distinguish the groups and were retained only if their p-value fell below .25. Next, retained PCs were entered into the model, one by one. It was tested whether a newly entered PC had an added value up and above the PCs already in the model. Additionally, already present PCs were removed if their contribution to the whole model became too low ($p > 0.1$). The Bayesian Information Criterion (BIC) was computed for each of these models and compared across models to find the best possible model fit. In the final modal, each PC was assigned a weight factor (ɑ).

Then, an intervention-related brain activation pattern (IP; comparable to the disease-related brain activation pattern in PET-studies; Alexander & Moeller, 1994) was constructed, in which the contribution of each voxel to the intervention-related activity (per PC; M) was weighted by the weight factor for the corresponding PC (ɑ; **4)**. The resulting IP can be interpreted as the brain areas in which the activity pattern of the intervention group is different from the reference group.

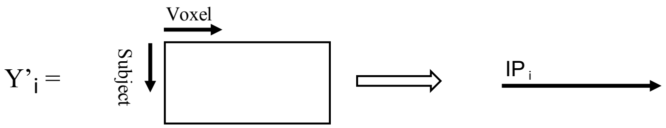


(4)

Following, a bootstrapping method (N = 1000 bootstraps) was applied to check the stability of the brain activation patterns extracted by the SSM/PCA.

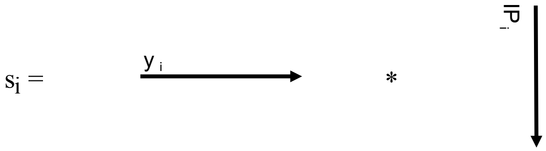
LOOCV

Lastly, a leave-one-out cross-validation (LOOCV) was conducted to examine whether the pattern extracted by the SSM/PCA could be used to classify individual subjects. For each subject (i), the SSM/PCA analysis was conducted without its data (y_i) being used to determine an intervention pattern (IP_i) (**5**).



(5)

Next, the left out subject (y_i) was projected onto IP_i resulting in a LOOCV score per subject. The subject's activity pattern was multiplied by the intervention pattern obtained by the SSM/PCA, resulting in a LOOCV score per subject (s_i; **6**).



(6)

This cross validation technique was used to ensure that the subject score was independent from the pattern it was derived from. The LOOCV scores of each subject are plotted in Figures 6.3, 6.5, and 6.7 in the results section. As individuals in the different study conditions were expected to differ from each other, it was hypothesized that, on average, activity patterns of subjects in the intervention groups would diverge from those of subjects in the reference group.

APPENDIX 12: BRAIN AREAS RESULTING FROM THE SSM/PCAS COMPARING THE 1) AEROBIC INTERVENTION GROUP AND CONTROL GROUP, 2) COGNITIVELY-ENGAGING INTERVENTION GROUP AND CONTROL GROUP, AND 3) AEROBIC AND COGNITIVELY INTERVENTION GROUPS (CHAPTER 6)

TABLE 12.1. Brain areas in which activity patterns can differentiate between the aerobic intervention group and the control group.

			MNI coordinates[a]		
Anatomical label(s)	Brodmann	Hemisphere	X	Y	Z
Deactivation[b]					
Inferior frontal gyrus	BA47	Left	-48	28	-6
Superior middle frontal gyri/medial frontal lobe	BA10	Left	-26	58	-2
Medial & lateral occipital gyri	Visual association cortex	Right	8	-80	-10
SMA, premotor	BA6	Right	8	12	66
	Caudate	Left	-12	22	2
Angular gyrus	BA39	Left	-54	-50	12
Parahippocampal gyrus	BA36	Left	-28	-10	-32
Cerebellum		Left	-44	-58	-42
		Right	36	-56	-42
Activation[c]					
Middle/inferior temporal gyri	Fusiform	Right	56	-44	-16

[a] Brain coordinates defined by the Montreal Neurological Institute (MNI), based on which the location of (de)activated clusters of voxels can be identified. [b] Brain areas showing deactivation in the cognitively-engaging intervention group as compared to the control group. [c] Brain areas showing increased activation in the cognitively-engaging intervention group as compared to the control group.

TABLE 12.2. Brain areas obtained when comparing the pretest-posttest differences maps of the cognitively-engaging intervention group and the control group. The control group was used as the reference category.

			MNI coordinates[a]		
Anatomical label(s)	Brodmann	Hemisphere	X	Y	Z
Deactivation[b]					
Superior middle frontal gyri/ middle frontal lobe	BA10	Left	-20	60	2
	BA10	Right	24	56	-6
Inferior frontal gyrus	BA47	Left	-44	28	-8
	BA47		48	36	-4
SMA, premotor	BA6	Left	-22	14	48
Superior middle frontal gyri/ medial frontal lobe	BA8	Right	40	12	52
Superior parietal lobule	BA7	Right	36	-46	50
Inferior parietal lobule	BA40	Right	54	-30	52
Cerebellum		Left	-32	-64	-40
		Right	22	-82	-38
Medial/lateral occipital gyri	BA19	Right	24	-84	-18
Activation[c]					
Primary visual	Primary visual	Left	-24	-70	6
Cingulate gyrus	BA23	Right	16	-58	22
Angular gyrus	BA39	Right	52	-56	44
	BA39	Left	-50	56	42
Inferior temporal gyrus	BA20	Right	60	-22	-30

[a] Brain coordinates defined by the Montreal Neurological Institute (MNI), based on which the location of (de)activated clusters of voxels can be identified. [b] Brain areas showing deactivation in the cognitively-engaging intervention group as compared to the control group. [c] Brain areas showing increased activation in the cognitively-engaging intervention group as compared to the control group.

TABLE 12.3. Brain areas obtained when comparing the pretest-posttest differences maps of the aerobic intervention group and the cognitively-engaging intervention group. The aerobic intervention group was used as the reference category.

			MNI coordinates[a]		
Anatomical label(s)	Brodmann	Hemisphere	X	Y	Z
Deactivation[b]					
Middle & inferior temporal gyri	Fusiform	Right	58	-42	-14
Middle temporal	BA21	Right	68	-16	-14
Cerebellum		Right	16	-38	-20
		Left	6	-52	-10
Superior parietal lobule	BA7	Right	36	-52	50
Temporal pole	BA38	Right	24	8	-32
	BA38	Left	-50	10	-20
SMA, premotor	BA6	Left	-50	-8	30
Activation[c]					
Medial & lateral occipital gyri	BA19	Left	-42	-74	-10
Medial & lateral occipital gyri: Visual association cortex	BA18	Bilateral	0	-72	24
Superior parietal lobule	BA7	Right	14	-64	32
Thalamus	Thalamus	Right.	10	-16	14
	Thalamus	Left	-8	-12	16
Inferior frontal gyrus	BA44	Right	56	18	16
Superior middle frontal gyri/ medial frontal lobe	BA10	Right	46	44	16
Cingulate gyrus	BA24	Bilateral	2	2	30

[a] Brain coordinates defined by the Montreal Neurological Institute (MNI), based on which the location of (de)activated clusters of voxels can be identified. [b] Brain areas showing deactivation in the cognitively-engaging intervention group as compared to the aerobic intervention group. [c] Brain areas showing increased activation in the cognitively-engaging intervention group as compared to the aerobic intervention group.

DANKWOORD

Daar issie dan: mijn proefschrift! Hoewel alleen mijn naam erop staat, kan ik uiteraard niet voorbijgaan aan een (groot) aantal mensen dat dit proefschrift mede mogelijk gemaakt heeft.

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Beste Esther, al de eerste keer dat ik je ontmoette vielen me de rust en vriendelijkheid die je uitstraalde op. Ik kan me niet voorstellen hoe mijn promotietraject er zonder jou had uitgezien. Je was er altijd als ik vragen had of tegen problemen aanliep, en nam dan alle tijd die nodig was. Als Slim door Gym projectleider moet het beslist niet makkelijk geweest zijn om te dealen met moeilijke scholen, interventieleerkrachten die een andere baan vonden en promovendi die altijd maar met problemen kwamen aanzetten (of die problemen al opgelost hadden voor je er überhaupt iets over kon zeggen). Je hebt me veel geleerd over hoe om te gaan met de chaos die onderzoek doen heet.

Beste Danny, hoewel je mijn dagelijks begeleider was, heb ik je beslist niet dagelijks gezien. Het was heel fijn dat ik altijd de deur bij je plat kon lopen met allerhande problemen, geklaag, maar ook enthousiaste verhalen. Je wijze adviezen en met name je caviakalender (altijd weer een verrassing welke foto er op zou staan) wisten me altijd weer op te beuren. Bedankt dat je met je 'APA nazi'- instelling altijd alle punten en komma's in mijn referentielijsten aanpaste.

Beste Irene, ik zou niet weten hoe ik zonder jou alle Slim door Gym heisa had moeten doorstaan. Ik heb de afgelopen jaren meer tijd met jou doorgebracht dan met wie dan ook. Ik zal die keer nooit vergeten dat we net de bus misten en een uur moesten lopen naar het dichtstbijzijnde station. Blijkbaar zijn er op het Friesche platteland iets minder mensen die van het openbaar vervoer gebruik maken dan in de grote stad. Fijn dat je later een auto kocht om het proces van scholen bezoeken en halve bouwmarkten vervoeren iets makkelijker te maken. Ik kan me geen fijnere medepromovenda voorstellen om zebra's en koeien mee te beoordelen, om mee te vechten met toetsenborden die niet werken, en om mee te klagen over kinderen die uit het niets ijzeren spalkjes in hun mond hebben.

Beste overige leden van het Slim door Gym consortium, Anna, Marck, Jaap, Joanne en Marsh, wat een hectiek hebben we samen meegemaakt. Het was in het begin even wennen om met zoveel mensen aan één project te werken, maar ik kan met 100% overtuiging zeggen dat ik daar ontzettend veel van geleerd heb. Wat was het eigenlijk mooi om met z'n elven één gezamenlijk doel te delen. Bedankt voor alle gezellige (en soms wat minder gezellige) Slim door Gym meetings. Beste Remco, officieel ben je dan misschien geen lid van het Slim door Gym consortium, maar je hebt er minstens net zoveel tijd en energie in gestopt als de rest van het team. Fijn dat je altijd kritisch meedacht met de opzet, uitvoering en afronding van het onderzoek. Zonder jou was het Groningse MRI-deel van het onderzoek beslist in de soep gelopen, resulterend in krantenkoppen als "Achtjarig kind vastgeplakt aan MRI-scanner tijdens onderzoek in het UMCG". Bedankt dat je altijd de tijd voor ons nam, en dat je het nooit teveel moeite vond om voor de zoveelste keer uit te leggen wat SSM/PCA ook alweer inhoudt.

Aan alle (en dat zijn er een heleboel) studenten, testleiders en interventieleerkrachten die het project tot een succes hebben weten te maken: vaak wisten jullie het nog beter dan ik (want hoe werkt een hartslagmeter ook alweer?). Misschien zijn wij zelf nog wel het meest slim door gym geworden van al het gesjouw met balansplanken en gegooi met tennisballen. Uiteraard ook een dankjewel aan alle scholen, directeuren, leerkrachten en leerlingen die zoveel tijd en energie in Slim door Gym gestopt hebben.

Lieve Alex, mijn therapeute, dating-coach, en Liefmans-maatje. Wat zijn we samen vaak geschrokken van plotseling binnenlopende collega's of lawaai makende kasten. Ik had me geen beter kantoorgenootje kunnen wensen. Wat moet je te stellen hebben gehad met al mijn gezeik over leerkrachten en over allerhande dingen uit de soap van mijn leven (gelukkig waren het ook vaak leuke dingen, toch?). Double A voor altijd.

In die vier jaar heb ik ook alle promotiestruggles mogen delen met mijn mede-PhD's van Onderwijskunde. Jullie zullen wel blij zijn dat jullie nu eindelijk niet meer verplicht zijn om de trap te nemen. Bedankt voor de gezellige koffiepraatjes, promotie-uitjes, en wijnmiddagen. Met een speciale dank voor Marij, mijn favoriete hotelkamergenootje. Ik vond je al tof toen ik na afloop van mijn eerste werkdag nog een eeuwigheid met je heb staan kletsen. Wat een geluk dat we op hetzelfde moment zijn gaan promoveren. Ik kan me geen betere collega voorstellen om broodjes rendiervlees mee te delen. En natuurlijk kan ik Monique niet vergeten. Het begon ooit met het verstoppen van paaseitjes en is, gelukkig, geëscaleerd tot dagelijks contact en samen op vakantie gaan. Onvoorstelbaar hoeveel kaartjes en chocoladerepen ik al van je heb gekregen. Laten we nog vaak samen genieten van thee, ijsjes, dekentjes op de bank en sangria. Fijn, gezellig, aangenaam. Ik ga je ontzettend missen.

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OVER DE AUTEUR/ ABOUT THE AUTHOR

OVER DE AUTEUR

Anne de Bruijn is geboren op 2 augustus 1991 te Oud Gastel, Noord Brabant. Nadat ze in 2009 haar Vwo-diploma behaalde, verhuisde ze naar Nijmegen om daar te starten met de Academische Lerarenopleiding Primair Onderwijs (ALPO) aan de Radboud Universiteit. Na twee jaar besefte Anne dat ze onderzoek doen leuker vond dan voor de klas staan en besloot ze verder te gaan met het reguliere bachelor-programma Pedagogische Wetenschappen en Onderwijskunde. Nadat ze voor haar bachelor-scriptie drie maanden onderzoek had gedaan aan de University of London, meldde ze zich aan voor de Research Master Behavioural Science. Gedurende deze master werd ze steeds enthousiaster over onderzoek naar sport en bewegen. Ze volgde extra-curriculaire vakken over sportpsychologie en bewegingswetenschappen en ze schreef haar masterscriptie in deze richting. Na het cum laude afronden van de Research Master heeft ze een master Onderwijskunde gevolgd. Hierin combineerde ze haar interesse voor sport met haar achtergrond in de onderwijskunde via een stage op de afdeling Bewegingsonderwijs van Stichting Leerplan Ontwikkeling (SLO).

Anne startte in 2015 met haar promotieonderzoek aan de Rijksuniversiteit Groningen. Tijdens haar PhD is ze actief geweest in verschillende commissies, heeft ze deelgenomen aan diverse summer schools, en presenteerde ze haar onderzoek op meerdere nationale en internationale congressen. In november 2018 werkte ze een maand aan de University of Bern, Zwitserland als visiting researcher. Momenteel is Anne werkzaam als *Educational Scientist* op de afdeling Training & Performance Innovations bij TNO, waar ze onderzoek doet naar fysieke, mentale en cognitieve prestaties van professionals bij defensie.

ABOUT THE AUTHOR

Anne de Bruijn was born on August 2nd 1991 in Oud Gastel, the Netherlands. After obtaining her secondary school diploma in 2009, she moved to Nijmegen to start with the academic teacher training program at the Radboud University Nijmegen. After two years she realized that she liked doing research better than being at the front of the classroom, and she continued the regular bachelor program Pedagogical and Educational Sciences. After a 3 month research internship at the University of Londen for her bachelor thesis, she applied for the Research Master Behavioural Science. During this master, her interest for research on physical activity and sports grew. She followed several extracurricular courses in the domains of sports psychology and movement sciences, and wrote her master thesis on this topic. After graduating cum laude from the Research Master, Anne followed a second master Educational Sciences in which she combined her interest in sport with her background in educational sciences during an internship at the department of Physical Education of Stichting Leerplan Ontwikkeling (SLO).

Anne started her PhD research at the University of Groningen in 2015. During her PhD, she actively participated in several committees, followed various summer schools, and presented her work at national and international conferences. In 2018 she visited Bern University, Switzerland for a month. Anne is currently working as Educational Scientist at the Training & Performance Innovations department of TNO, where she is doing research on physical, mental, and cognitive performance of defense professionals.

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