The brain in motion

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GENERAL INTRODUCTION
CHAPTER 1

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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