Physical activity and cognition in children

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General introduction

"When you play outside a lot, your brain can explore the world, what it's like"
(10 year old boy)

Just like this 10 year old boy mentions in response to a question "why do you think physical activity and brain function are related?", most individuals are aware of the fact that our physical activity and physical fitness are related to our brain fitness. Already the ancient Greek and Roman philosophers mentioned the link between the body and mind with "mens sana in corpora sano" (although this was mentioned in a slightly different context) (Tomporowski, Lambourne, & Okumura, 2011). Yet while the health benefits of physical activity on children's physical development have been studied extensively, only recently researchers have started to study the relationship between physical activity and children's cognitive abilities, and to explore the possible underlying processes that can explain these findings. In this thesis, the relationship between physical activity, physical fitness and cognition will be studied. In addition, a physical activity intervention program was developed and implemented during lunch recess at several primary schools, and effects of this increase in physical activity on physical fitness and cognition were investigated. This provides insight into the complex relationships between physical activity, physical fitness and cognition in children, as well as effects on physical fitness and cognition when physical activity is manipulated.

1.1 Theoretical background

Physical activity, physical fitness and cognitive performance

Humans are born to be physically active. Our bodies are designed to move. Physical activity comprises all bodily movement produced by the muscular system that increases energy expenditure above normal physiological demands (Ortega, Ruiz, Castillo, & Sjöström, 2008). From an evolutionary perspective, movement of the body is a central concept in the development of cognition (Llinas, 2001). Cognition is a very general term that reflects a number of underlying mental processes (Tomporowski, Davis, Miller, & Naglieri, 2008); e.g. perception, attention, executive functioning, intelligence, and academic achievement. It is through movement that we gradually come to understand, predict and anticipate the outcome of behavior. Physical activity and sensorimotor experience may thus be necessary for optimal neural development in children (Piaget, 1952). Young infants learn how to reach, sit, walk and run by experiencing and exploring a wide range of movements (Spencer et al., 2006). Most children have developed fundamental movement skills by the time they enter school at around age 4, which allows them to play physically active games with their peers. As children grow older, they will continue to explore by means of unstructured activities during free play time, and can develop and master more complicated movement skills during physical education or participation in organized sport and exercise. This will be beneficial for their general health and mental well-being. More specifically, involvement in repetitive and structured physical activity could increase children's physical fitness. Physical fitness is a set of attributes associated with the capacity to perform a variety of physical activities (Ortega et al., 2008), and consists of several dimensions like muscular strength, muscular endurance, speed, and cardiovascular endurance. While physical fitness has a strong genetic component, regular involvement in physical activity is essential for promoting physical fitness of children (Strong et al., 2005). It promotes development of the cardiovascular and musculoskeletal system. In addition, the physiological stress as a result of physical activity will be present in the brain, and can promote brain function. This has already been demonstrated in research on adults, which shows that physical activity enhances learning and memory (Hillman, Erickson, & Kramer, 2008), and might be even more important when the brain is still developing rapidly, as is the case in school aged children. The cognitive functions that show the largest benefits of physical activity are those that require extensive amount of cognitive control, i.e. executive functions. In this thesis, the focus is on these executive functions; the relationship with and the effects of physical activity and physical fitness on executive functions in children (Figure 1.1). In addition, academic achievement in children is studied, as the development of executive functions and academic achievement are closely related (Best, Miller, & Naglieri, 2011).

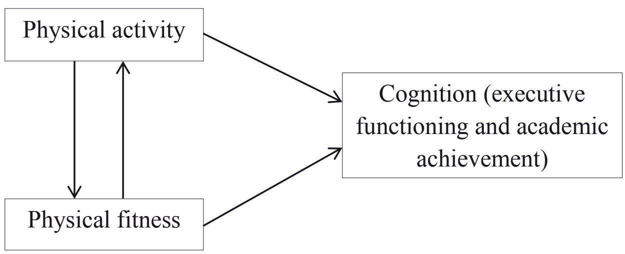

Figure 1.1. Hypothesized relations as examined in this thesis.

Executive functioning and academic achievement

As children develop, they become increasingly able to control their thoughts and actions, which has been associated with the development of executive functions (Friedman et al., 2008; Pennequin, Sorel, & Fontaine, 2010). Executive functions refer to various cognitive processes used to regulate goal directed interaction with the environment, especially in non-routine and unstructured situations (Banich, 2009). While executive functioning is an umbrella term that includes a wide range of skills and abilities, it is considered to include four core abilities; inhibition, working memory, cognitive flexibility, and strategic planning (Anderson, 2002; Miyake et al., 2000). Executive functions are essential for interaction in normal daily activities. Moreover, executive functions are related to creativity (Scibinetti, Tocci, & Pesce, 2011), and the emergence of theory of mind (Carlson, Moses, & Breton, 2002). Executive functions develop rapidly through childhood, and are clearly correlated with the maturation of the frontal lobes, in particular the prefrontal cortex; both psychological and neurobiological models of executive functions have suggested the close linkage between the development of executive functions and the refinement of prefrontal cortical circuitry (Best & Miller, 2010; Diamond, 2002). The prefrontal cortex shows several critical periods of development; during the first year of life, between 3 to 6 years, and during preadolescence, between 7 to 12 years of age (Anderson, 2002; Diamond, 2002). Therefore, it is likely that executive functioning might benefit from physical activity during the preadolescent years. This, in turn, might also be beneficial for academic achievement. Academic achievement is related to school performance, and is most often expressed as academic grade or score on standardized tests of mathematics, reading and spelling. Mathematics, reading and spelling are complex skills that require a child to effectively plan, update working memory, shift attention or inhibit impulsive behavior (Best et al., 2011). Executive functions are thus essential for academic achievement. In addition, the development of executive functioning goes together with the development of language (Ardila, 2013).

Language and executive functioning

As executive functioning is about the processes that control and regulate thought and action, language plays an important role in executive functioning processes. Inner speech (talking to oneself) seems crucial to apply and evaluate decisions, or to hold and manipulate information in mind. Indeed, language is seen as a cornerstone in the development of executive functioning (Ardila, 2008). Language is a complex social behaviour that includes multiple processes related to sensory, motor and cognitive skills (Jacob, 2013; Knudsen, 2004). Language development represents a powerful instrument to accumulate and transmit knowledge about the world, and is crucial for the initiation and maintenance of interpersonal relationships (Marton, Abramoff, & Rosenzweig, 2005). Children with developmental language disorders (DLD) are characterized by delayed language in the absence of a mental or physical handicap or a specific sensory or emotional cause (Bishop, 1992). The prevalence of language delay in children in the Netherlands has been estimated to be between 5 and 10% (Reep-Van den Berg, De Koning, De Ridder-Sluiter, Van der Lem, & Van der Maas, 1998), and is more likely to affect boys than girls. As language and executive functioning are intertwined, children with DLD also experience difficulties with executive functions (Henry, Messer, & Nash, 2012; Vugs, Hendriks, Cuperus, & Verhoeven, 2014). In addition, they show lower motor skill performance, which might be the result of a genetic risk or neurologic deficit, or of less or less varied physical activity, as communication difficulties will negatively influence social acceptance and participation in play activities. It is interesting to investigate the physical activity and physical fitness levels of children with DLD, as physical activity may be a tool to improve executive functioning in children with DLD. In this thesis, both typically developing children and children with DLD are included.

Previous research on physical activity and executive functioning

Within neuropsychology, which is the study of brain-behavior relationships, executive functioning is a relatively new term that was first mentioned as a subdomain of cognition by Luria in 1966 (Ardila, 2008). However, the idea that there was something like "higher" order cognition dates back from late 19th and early 20th century, when clinical investigators documented diverse behavioral disorders in cases of frontal pathology (e.g. the story of Phineas Gage) (Ardila, 2008). Based on adults with frontal injuries and experimental lesions studies, a basic understanding emerged on the role of executive functioning in adults. Neuropsychological tests were developed to detect deficiencies in normal brain function (Pennington & Ozonoff, 1996). Only in the late 1980s researchers started to focus on executive functioning development in children, at first in children with frontal lobe lesions (Espy & Kaufmann, 2002). From the mid-1990s, a growing body of research gradually emerged on executive functioning development in typically developing children, and on the beneficial effect of exercising the body on the performance capabilities of the brain. In the last decade, a few studies have shown a positive relationship between *physical fitness* and executive functioning in children; children with better performance on a physical fitness test also show better performance on tests measuring executive functioning (Buck, Hillman, & Castelli, 2008; Chaddock et al., 2010). In addition, neuroimaging studies on brain structure and function (e.g. EEG, fMRI) show that fitter children or more active children display larger volumes of specific regions of the basal ganglia and hippocampus, and show greater P3 amplitude during executive functioning tests than their less fit or active peers, indicating better working memory and inhibitory capacity (Chaddock et al., 2010; Kamijo, Takeda, & Hillman, 2011; Pontifex et al., 2011). Furthermore, a few studies have shown positive effects of *physical activity* on aspects of executive functioning performance in children, both immediately after exercise (acute effects) (Hillman et al., 2009) as well as effects resulting from multiple bouts of exercise (chronic effects) (Davis et al., 2011; Kamijo et al., 2011). Nevertheless, research on the effects of physical activity on executive functioning in children is still limited, and the mechanisms explaining the possible effects are subject of debate.

Neurobiological pathways

Regular aerobic exercise at a moderate to vigorous intensity appears specifically to enhance executive functioning, but involvement in cognitively engaging physical activity can stimulate executive functioning as well. Several mechanisms are mentioned to explain the relationship between physical activity and executive functions. They can broadly be categorized in physiological mechanisms and learning/developmental mechanisms. The physiological hypothesis states that aerobic exercise induces certain physiological changes in the brain as a result of increased physical fitness. Aerobic exercise places a demand on the body's cardiovascular system; there is an increase in the ability of the heart to deliver oxygen to the working muscles. However, aerobic exercise will also lead to an increased cerebral blood volume and will stimulate the release of neurotransmitters; both animal and human research show increased levels of neurotransmitters like brain-derived neurotrophic factor (BDNF) and other growth factors, that promote neurogenesis and synaptic plasticity (Hötting & Röder, 2013). In addition, research in humans shows increased regional cerebral blood volume in a specific area of the hippocampus involved in memory performance (Pereira et al., 2007). The beneficial effects of physical activity on cognition might thus be mediated by these physiological factors. Other mechanisms explaining the relationship between physical activity and cognition focus on the cognitive demands apparent in goal-directed exercise. When children are engaged in physical activities, these activities often take place in a complex and constantly changing environment.

The cognitive skills acquired during physically active free play and games will perhaps transfer to skills used during executive functioning tasks, or to skills apparent in words and mathematical operations. Also, learning new movements or being confronted with new situations as a result of making movements, require complex cognition (Best, 2010). This places a high demand on cognitive processes, including executive functions. Animal research suggest that environmental enrichment and complex learning tasks can promote the survival of new neurons (Kempermann et al., 2010), confirming the importance of cognitively engaging physical activity. The physiological and cognitive demand pathways might be additive, which would mean that a combination of both aerobic exercise and complex activity will lead to the biggest positive effects (Kempermann et al., 2010). Therefore, in the current study a combination of both exercises is included in the physical activity intervention program.

1.2 Objectives and outline of this thesis

The aims of this thesis are to 1) to examine the relationship between physical activity, physical fitness, executive functioning and academic achievement in primary school children aged 8-12 years, and 2) to study the effects of manipulating physical activity levels of children on physical fitness and executive functioning. Both typically developing children and children with DLD are examined.

In Chapter 2, relationships between physical fitness, executive functioning, and academic achievement are studied in typically developing children. More specifically, it is investigated if executive functioning has a mediating role within the relationship between physical fitness and academic achievement. While there are studies linking physical fitness to either executive functioning or academic achievement, it is valuable to investigate those relationships together. This is done by creating structural equation models, in which the relations between physical fitness, executive functioning and academic achievement are examined simultaneously. Physical fitness, executive functioning and academic achievement are factors that consist of several aspects that can be measured. Therefore, prior to the main analysis of the relationships between those three factors, it is necessary to perform confirmatory factor analysis to test whether the observed measures are good indicators of each factor. Measures of aerobic fitness are often used in studies relating physical fitness to cognition, however, in this study also strength components of physical fitness are included. Executive functioning and academic achievement are measured with neuropsychological tests and the child academic monitoring system.

The aim of Chapter 3 is to examine the relationships between objectively measured daily physical activity and performance on core aspects of executive functioning in typically developing children. Daily physical activity of children, which means the typical activity pattern of children in daily life, can be measured with an accelerometer that children wear all day long, for several days. This is important to investigate, as habitual physical activity of children consists of long periods of time spent sedentary, alternated with physical activity at low intensity, and short bursts of moderate to vigorous physical activity. Chapter 3 gives insight into the time spent in different intensity levels in children, which are then related separately to their performance on executive functioning measures.

Chapter 4 focuses on children with developmental language disorders. As communication is very important to get involved in activities that require social interaction, it might be expected that children with DLD show lower physical activity and physical fitness levels compared to typically developing children. Therefore, in this study physical activity and physical fitness levels of children with DLD are compared to those levels of typically developing children. In addition, physical activity is related to performance on the physical fitness measures in both groups of children. So far, no studies have evaluated the developmental profile of children with DLD across physical activity and physical fitness domains.

Chapters 5 and 6 describe the effects of a physical activity intervention program on physical fitness and executive functioning of respectively typically developing children and children with DLD. While the physical activity intervention program for typically developing children was provided twice a week during lunch recess, children with DLD followed the intervention program as part of the regular school day. In both instances, the physical activity program was run for 22 weeks. In these chapters, baseline and posttest scores on physical fitness and executive functioning of children in the intervention group are compared to those scores of children in a control group who did not follow the physical activity intervention program. Results can provide insight into effects of increased physical activity on physical fitness and executive functioning in children. The possible mechanisms explaining the relation between physical activity and executive functioning are also discussed. In addition, Chapter 6 explores whether physical activity offers an alternative way to improve executive functioning in children with DLD, who experience difficulties in both language and executive functioning performance.

Finally, a summary and general discussion are provided, in which the results of the studies in this thesis are discussed more generally in the light of the theory as described in this introduction. In addition, critical reflections are made on the theoretical background, and on the methods used in this study. Suggestions for further research are provided, in order to strengthen the importance of promoting children to be physically active. Children need to have the opportunity to explore the world through physical activity, because, just like the boy said, only then the brain can understand how it is to act in this complex world.

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