Bachelor thesis Psychology & Health

Cognitive Neuroscience and Clinical Neuropsychology

The Effect of Physical Activity on Executive Functioning in Children and Adolescents: a review

Specification of the conditions under which physical activity enhances executive functioning in terms of type, duration and intensity level

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Words: 10747

Words (tables and references included): 15761

Bachelor thesis Psychology & Health, Cognitive Neuroscience and Clinical Neuropsychology

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Tilburg University

Date: June 2013

Abstract

Aim of this review is to specify the conditions under which physical activity benefits executive functioning in younger healthy populations, including school age children and adolescents. Intervention studies on the relationship between physical activity and executive functioning in children and adolescents are systematically identified and reviewed, distinguishing between different *type*, *duration* and *intensity level* of interventions. This review found substantial evidence for a beneficial effect of both acute and chronic physical activity interventions on a wide range of executive functions, with physical activity high in cognitive and social interaction demands showing the greatest beneficial effects. There is tentative evidence indicating that engaging in physical activity over a longer period each day benefits executive functioning to a greater extent. Furthermore it seems that a certain level of intensity of physical activity is necessary to effectively alter executive functions. The sustainability of the beneficial effects remains to be explored, however results of this review are useful in designing physical activity interventions that are applicable in practical contexts.

Keywords

Executive functioning, physical activity, children, adolescents, type, duration, intensity level, sustainability

Content

1. Introduction

1.1 The effect of physical activity on cognition a historical perspective

That physical activity has a positive effect on our body and benefits our psychological well-being is not entirely new. However, it took a long time before it became evident that physical activity not only causes a healthier body but also a healthier brain. For many years, the notion that physical activity improves our cognitive functioning has been doubted and it has been seen as a very radical one. Until 1975, when Spirduso showed that older men with a lifestyle of regular physical activity performed better on a range of reaction and movement tasks compared to men of similar age with a non-active lifestyle. The older active men did even better than much younger non-active men. A lifestyle of physical activity thus appeared to play a more dominant role in determining reaction and movement time than age. Since then hundreds of publications describing the relationship between physical fitness and cognition have appeared. In the first years, especially cross-sectional studies have been reported and these concluded that people with a lifestyle of regular physical activity, have better cognitive abilities than people with a non-active lifestyle. However, a risk of these cross-sectional designs is that the reported effects may reflect some other factor than the activity level. With that other factor being able to explain the relationship between physical activity and executive functions (e.g., nutrition, genetics, education). For example it is plausible that not engaging in physical activity goes along with other unhealthy habits such as smoking or an unhealthy diet and that the people who choose to engage in physical activity already possess better cognitive capacities (Sitskoorn, 2004). Because of these reasons prospective research or randomized controlled trials, with participants who are at baseline similar in both cognitive and other variables, form a better research method to study the relationship between physical activity and executive functioning.

In the 90s lots of longitudinal studies were reported with older people divided into aerobic exercise- and control groups. However, these studies yielded inconclusive results (Kramer et al., 2004). Interpretation of these early studies was difficult because the studies differed in duration, intensity and type of the exercise training and in age, health and fitness level of the participants used to measure the cognitive improvements.

To shed light on the relationship between cognition and physical activity Colcombe & Kramer (2003) conducted a meta-analysis of eighteen intervention studies on older adults (1966-2001) and researched which cognitive processes benefited most from aerobic exercise interventions. Two important conclusions can be drawn from this research. First, physical activity indeed has a significant positive effect on cognitive functioning in older people. Second, although there are effects of physical activity on a wide range of cognitive functions executive control tasks in particular benefited from physical activity. Thus, of all cognitive functions, executive functions, instead of basic perceptual and motor skills, are most susceptible to physical activity interventions in older adults.

1.2 Executive functioning

Barenberg, Berse, & Dutke (2011) reviewed that the conceptualization of executive functions has changed from that of a global cognitive control system to that of specific executive functions of attentional control. Executive functioning is crucial for human survival in our everyday life because it is found in all our cognitive, emotional and motor functioning, including the ability to work and attend school, function independently at home, or develop and maintain appropriate social relations (Chan, Shum, Toulopoulou, & Chen, 2008). According to Chan et al. (2008) executive functioning is “a term comprising a wide range of cognitive processes and behavioural competencies which include verbal reasoning, problem-solving, planning, sequencing, the ability to sustain attention, resistance to interference, utilization of feedback, multitasking, cognitive flexibility, and the ability to deal with novelty” (p.201). Thus executive functioning is not a single entity but rather a ‘catch all- or umbrella term’ consisting of many subcomponents. According to Lezak (1995) the main components of executive functioning are reducible to; volitition-our capacity for intentional behaviour, planning-our ability to ‘look ahead’, purposive action-our ability to initiate, maintain, switch & stop sequences of complex behaviour and effective performance-our ability to self-monitor. In contrast, Miyake et al. (2000) identified three separable components of executive functioning by latent variable analysis; mental set shifting (“shifting”), information updating and monitoring (“updating”), and inhibition of prepotent responses (“inhibition”). The exact differentiation of the subcomponents is still a matter of debate but important to keep in mind while reading this review is the diversity of the concept of executive functioning.

Because of this diversity, there is no standard test to assess executive functioning in general, rather the different sub aspects of executive functioning are assessed using different tasks (Banich, 2009). Banich (2009) defines executive functioning as “the set of abilities required to effortfully guide behaviour toward a goal, especially in *nonroutine* situations” (p.89). The challenge for researchers is to create such a nonroutine situation while testing executive functioning by transferring goal setting, structuring and decision making from the clinician to the participant (Lezak, 1995).

The research on the nature of executive functions goes far back in history and has its historical roots in studies of patients with frontal lobe damage (Miyake et al., 2000). The most famous and well-known of these patients being Phineas Gage (Damaiso, Grabowski, Frank, Galaburda, & Damaiso, 1994). Patients with frontal lobe damage have problems functioning in their everyday lives. Although their performance on a wide range of neuropsychological tests remains stable, they exhibit large impairments in their ability to perform on tasks that tap into executive functions (Miyake et al., 2000). Today therefore most researchers accept that networks comprising the (pre) frontal cortex are critical for executive functioning (Jurado & Roselli, 2007). However, theories regarding the exact neural mechanisms associated with executive functioning are contentious and hence more research on this field is clearly necessary (Banich, 2009).

1.2.1 The development of executive functioning

Jurado & Rosselli (2007) reviewed that the development of executive functions account for a great deal of the differences observed between healthy people in different stages of development. As children grow older they show better performance on tasks that tap into individual components of executive functioning and on tasks that require the coordination of multiple components (Diamond, 2006). The observed improvement in executive functioning is accompanied by growth spurts in the neurophysiological maturation, particularly synaptogenesis and myelination, of the frontal lobes (Anderson, 2002). However, the separable executive functions follow different developmental pathways and mature at different rates with many functions maturing only in adolescence or early adulthood (Anderson, 2002). On the other hand with ageing there is an observed decline in executive functions (West, 1996).

In summary, executive functions are known to develop late (throughout childhood and adolescence) and decline early over the course of healthy aging. Moreover these observations are plausible when taking into account the developmental time course of our brain structures. The brain regions critical in executive functioning are still immature during childhood (Anderson, 2002). In addition those brain areas involved in executive functioning are vulnerable to the effects of ageing and decrease in volume along with other anatomical changes when we are growing older (Raz & Rodrique, 2006).

1.3 Physical activity

Frequently used terms in physical activity research are ‘physical fitness’,’ physical activity' and 'exercise' (Barenberg et al., 2011). These terms are used interchangeably but it is important to notice that they describe very different concepts (Caspersen, 1985).

Caspersen (1985) describes physical fitness as "a set of attributes that people have or achieve and that are either health related (e.g., cardiorespiratory endurance, oxygen supply) or skill-related (e.g., coordination of motor responses)" (p.126). These attributes are measurable components describing an individual's ability to engage in physical activity.

Physical activity is defined by Caspersen (1985) as "any bodily movement produced by skeletal muscles that result in energy expenditure" (p.126). Physical activity contains many subcategories, including leisure activities, sports, household activities and exercise. According to Caspersen (1985) exercise is "a subset of physical activity that is planned, structured and repetitive and has as a final or an intermediate objective the improvement or maintenance of physical fitness" (p.126). Moreover, physical activity and exercise are frequently applied interventions, with physical fitness as an outcome measure (Barenberg et al., 2011).

Howley (2001) distinguished between aerobic exercise "exercise that involves large muscle groups in dynamic activities that result in substantial increases in heart rate and energy expenditure" (p.364) and resistance exercise "exercise (training) designed specifically to increase muscular strength, power, and endurance by varying the resistance, the number of times the resistance is moved in a single group (set) of exercise, the number of sets done, and the rest interval provided between sets" (p.365). Regular participation in aerobic exercise enhances the function of the cardiovascular system (Howley, 2001).

Most studies on the relationship between physical activity and exercise focus on aerobic exercise. Guiney and Machado (2013) mention the follow reasons "it is readily accessible, requires no specialist knowledge or equipment, and is more directly linked to cardiovascular fitness, which in line has been linked to executive functioning capabilities" (p.74).

As mentioned above physical activity consists of many subcategories that vary in terms of *type, intensity* and *duration*. The type of physical activity can be anything, simple walking or cycling or a complex modified soccer intervention for example (Barenberg et al., 2011). According to Barenberg et al. (2011) the level of intension can generally be defined as "a certain percentage of the individual's maximum workload, as measured by oxygen uptake or heart rate assessments for instance" (p.210). A commonly used indication of maximum heart rate (MHR) is the formula 220-age. Three target zones of physical activity intensity based on a percentage of your maximum heart rate are light (55-64% of maximum heart rate), moderate (65-74% of maximum heart rate) and vigorous (75-90% of maximum heart rate)

(Physical Activity Resource Centre, 2003). The duration of an intervention can vary from a single bout of physical activity, to interventions consisting of several weeks or even months of exercise (Barenberg et al., 2011).

1.4 The link between executive functions and physical activity.

The meta-analysis of Colcombe and Kramer (2003) was crucial in the development of the idea that executive functions are enhanced by physical activity. In almost every article about the topic the authors refer to the review of Colcombe and Kramer. This meta-analysis formed the starting point for further research and numerous studies have since addressed the relationship between executive functioning and physical activity (Barenberg et al., 2011). First, the beneficial effect of physical activity on executive functioning was reported in older adults and people with executive deficits. In older adults improvements have been reported for performance on standard clinical tests of executive functioning, including the Wisconsin card sorting task (Albinet, Bouchard, Bouquet, & Audiffren, 2010), the Stroop Task (Smiley-Owen, Lowry, Francois, Kohut, & Ekkekakis, 2008) and the REY Auditory Verbal Learning Test (Kramer et al., 2001). For people with executive deficits improvements in executive functioning after physical activity were found for Parkinson patients (Tanaka et al., 2009) and Alzheimer patients (Rolland, Abellan van Kan & Vellas, 2008).

However, an increasing number of studies with healthy adults (Masley, Roetzheim, & Gualtieri, 2009; Sibley, Etnier, & Le Masurier, 2006; Guiney & Machado, 2013; Verburg, Könings, Scherder, & Oosterlaan) and children (Best, 2010; Davis et al., 2011; Guiney & Machado, 2013; Verburg et al., 2013) has shown that physical activity not only compensates for executive deficits in people with cognitive impairments, but it also enhances executives functions in healthy populations. Thus, evidence suggests that physical activity enhances executive functioning even when the brain and executive functioning systems are still developing.

The aim of this review is to aggregate the research done until now on the effect of physical activity on executive functions of younger healthy populations, including school children and adolescents. Previous reviews (except Best, 2010) that focussed on healthy populations included not only children and adolescents but also young adults (Verburg et al., 2013) and older adults (Barenberg et al. 2011; Guiney & Machado, 2013). In this review the focus is only on children and adolescents. Research on these younger healthy populations is highly relevant because in these age groups the frontal lobes and executive functions are still developing. If physical activity has a positive impact on the developing brains, individuals may benefit from it for the rest of their lives. Moreover, executive functions are related to learning processes relevant in education (Barenberg et al., 2011) and similarities exist in the brain networks that underlie cognitive control and academic achievement (Hillman et al., 2009). If one can enhance executive functions and thus academic performance of children and adolescents with the simple and inexpensive method of physical activity interventions, more research on this field is more than welcome.

Adolescence is a confusing term used in the literature for a broad range of persons of different ages. According to De Wit, Slot & Van Aken (2004) adolescence is the period between the onset of puberty and adulthood in which the person develops their own identity. It is very difficult to pinpoint an exact age limit to this phase, due to large inter individual differences of adolescents. From a practical approach there can be stated that adolescence ranges from 10 years of age to 22 years of age, with a subdivision of early adolescence (10-13 years), middle adolescence (14-18 years) and late adolescence (19-22 years) (De Wit, Slot & Van Aken, 2004). Therefore, research on the effect of physical activity on executive functioning in healthy individuals up to the age of 22 is included in this review.

Until now researchers have used a diversity of physical activity interventions to answer the question if physical activity enhances executive functioning in children and adolescents. The physical activity interventions varied remarkably in *type*, *intensity level* and *duration* of the physical activity. It is plausible that not all of these different interventions have the same effect on executive functioning. For example, tentative evidence that cognitively-engaging exercise enhances executive functioning to a greater extent than non-cognitively-engaging exercise is presented in the review of Best (2010).

Although a few recent reviews have described the effect of physical activity on executive functioning in younger healthy populations, none of these reviews shed light on the question under which circumstances physical activity enhances executive functioning. Therefore, in this review the research on the effect of physical activity on executive functions is reviewed with the intention to specify the conditions under which physical activity benefits executive functioning in children and adolescents regarding type, duration and intensity level. Specification of the conditions under which physical activity enhances executive functions in young healthy populations is necessary in designing physical activity interventions that are applicable to practical contexts in real life.

Apart from this, none of the earlier reviews explored the sustainability of the beneficial effects of physical activity interventions on executive functioning. However, it is important to know the duration of the beneficial effects of physical activity interventions on executive functions. For example, is continued physical activity needed to achieve permanent beneficial effects in executive functioning? To answer this question I will also consider the sustainability of the beneficial effects on executive function of either intervention. My hypothesis is that the physiological changes produced by long-term interventions are more structural and therefore chronic physical activity interventions have more sustainable effects on executive functioning.

2. Method

2.1 Literature Search

The literature search was performed in March and April 2013. Relevant publications on the effect of physical activity on executive functioning of schoolchildren and adolescents were identified by extensive literature research in the psychological and medical databases: PsychInfo, MedLine and PubMed. To get access to full texts the databases Google Scholar and Science Direct were used.

The following terms were combined as search keys: executive function* (or substitute executive processes) AND physical activ* (or substitute exercise). The search on executive funct* AND physical act* produced over 100 unique studies and the search on executive funct* AND exercise produced even more than 200 unique studies. First the titles, then the abstracts and eventually the full texts of the identified publications were carefully examined for possible inclusion in the analysis.

2.2 Inclusion criteria

The identified studies had to meet the following inclusion criteria: experimental studies (no reviews), studies focusing on healthy populations of children and adolescents, studies focusing directly on the relationship between physical activity and executive functions (instead of discussing these in context of other variables), intervention studies with pre/post comparisons and with behavioural instead of physiological or neuroelectrical outcome measures. Most articles were excluded because they did not cover the relevant topic, focused on (older) adult populations or had a cross-sectional design.

Eventually the sample was reduced to 15 articles. 10 additional articles were identified through cross-references. Finally 25 articles were included in this literature review. Earlier reviews on the relationship between executive functioning and physical activity were carefully examined to determine the additional value of the current review. There is some overlap in studies used in this review and earlier reviews on this topic. All but two of the studies included in the review of Best (2010) are also included in this review. Thirteen studies included in this review were also included in a recent review of Verburg et al. (2013). Four of the studies included in this review were also used in the review of Barenberg et al. (2011), and three of the studies used in this review were included in a recent review of Guiney & Machado (2013). In summary, 17 studies included in this review have been included in an earlier review and 8 studies have to my knowledge never been included in another review before.

3. Results

3.1 Acute physical activity interventions

Sixteen studies examined the effect of acute physical activity interventions on executive functioning in children and adolescents. Twelve of these studies did find an effect of acute physical activity on executive functioning.

As stated earlier executive functioning is an umbrella term comprising a wide range of cognitive processes and behavioural competencies. Using acute physical activity interventions, effects on many different types of executive functioning have been found.

Hillman et al. (2009) investigated the effect of an acute bout of 20 minutes treadmill walking at 60% of estimated maximum heart rate on inhibitory control, measured with a modified Erikson Flanker Task as heart rate returned within 10% of pre exercise level. In 20 preadolescent children (average age 9,5) general response accuracy increased significantly after treadmill walking. With the incongruent trials, those requiring greater amounts of inhibition, benefitting the most. No such effects were observed for reaction time, indicating that 20 minutes of treadmill walking did not alter the speed of the children's responses. Moreover, the children showed increased performance in reading comprehension. However, it should be noticed that the sample size was small (n=20) and therefore the results have to be interpreted carefully. Ellemberg, & St-Louis-Deschênes (2010) found that 30 minutes of stationary biking benefitted performance on a choice response time task in both 7 and 10 year old boys. The beneficial effects were equal for both age groups. Tine and Butler (2012) indicate that 12 minutes of running at 70-80 % of maximum heart rate increased selective attention as measured with the D2 Test of Attention in 164 children aged 10-13 years. Moreover, selective attention improved to a greater extent in children from lower-income families than in children from higher-income families. However, at the pre-test of selective attention no effect of income level was found. The results showed that children with low baseline scores on selective attention benefitted more from the physical activity intervention than those with high baseline scores. Similar results are obtained by Sibley & Beilock (2007), they measured the effect of 30 minutes of vigorous intensity treadmill walking on working memory measured with the Operation Span and Reading Span tasks in 48 participants (average age 21,5). They divided participants into four equal quartiles (n=12) based on their average performance on the working memory tasks at baseline. Exercise enhanced working memory from baseline to post test but only for individuals with the lowest working memory at baseline (lowest quartile group). Thus individuals with the lowest working memory abilities benefit the most from a physical activity intervention. The order of the baseline session and exercise session was counterbalanced across participants and heart rate intensity during exercise was the same for the for the four quartiles strengthening the interpretability of the results.

Cooper, Bandelow, Nute, Morris, & Nevill (2012) displayed mixed findings. They did find an effect of a 10 minute shuttle run intervention on working memory as measured with the Sternberg Task, but not on executive control as measured with the Stroop test in 45 12-13 year old adolescents. They found improvements in response times on the Sternberg task, but no improvement in response accuracy was observed. The improvements in response times were similar across two different domains and all complexity levels, suggesting that the improvements are most likely a result of a general speeding up of responses across multiple cognitive domains. A limitation of this study is that the effect of the acute physical activity is tested only 45 minutes after the intervention and not for shorter intervals. There may be an effect of 10 minute shuttle run on Stroop performance that persists for less than 45 minutes. Pirrie & Lodewyk (2012) also showed a pattern of mixed findings. They observed an improved performance on a Trial Making Test assessing planning ability but failed to observe an improvement in attention as measured with a Stroop like task in two classes of fourth-grade students (n=40), after 20 minutes of moderate to vigorous physical activity (within a 45 minute physical education lesson). Children for example had to perform a list of activities posted on the wall as quickly as possible (e.g. “touch every circle in the gym with one knee” p.95)). Also no effects were observed for simultaneous processing which measured immediate recall, or successive processing. The conditions PA/ rest were counterbalanced and therefore greatly strengthened the interpretability of the results. However, the interaction between class (the classes followed a reversed schedule; first PA or first rest) and treatment was significant for planning, attention and simultaneous processing, suggesting that retesting with the same cognitive test is an important confounder of the results. Eventually important to notice is that the cognitive tests were not counterbalanced and therefore planning ability was always conducted first. It is possible that the impact of the physical activity intervention had already declined when the other cognitive abilities were measured.

Five of the sixteen studies failed to find an effect of an acute bout of physical activity on measures of executive function. Gothe, Pontifex, Hillman, & McAuley (in press) indicated that performance on a modified Erikson Flanker Task and the N-back task after 20 minutes of treadmill walking was the same as after 20 minutes of rest in 30 females with an average age of 20 years. The failure to observe a beneficial effect following the aerobic condition may be attributable to methodological aspects. Cooper et al. (2012) and Pontifex, Hillman, Fernhall, Thompson, & Valentini (2009) did find beneficial effects of acute aerobic exercise on working memory as measured with the Sternberg task, which taps into maintenance processes of working memory. However, Gothe et al. (in press) used a N-back task and this task taps into a different component of working memory, i.e. manipulation processes. Another explanation cited by the authors for the observed pattern of results is that the beneficial effect of aerobic physical activity is gender specific and this is the first study that conducted the research on a homogenous sample of females. The study has a small sample size and therefore its results need to be carefully interpreted. Tomporowski, Davis, Lambourne, Gregoski, & Tkacz (2008) showed that 15 minutes of treadmill walking did not influence the global switch costs (time required to switch performance from one task to another) or error rates on a Visual Switching task in 69 sedentary overweight children aged 7-11. They also indicate that physical activity did not have a differential effect on switch task costs for younger and older children. However, it has to be taken into account that the participants were overweight and it is plausible that overweight and inactive children experience exercise differently than their fitter peers do. Moreover, they did not specify the intensity level of the treadmill walking intervention. They only state that treadmill speed was 3 mph with a grade of 3% and that this exercise bout was designed to elicit an aerobic response in sedentary children. However, they did not report if the physical activity demands actually showed to be sufficient to elicit an aerobic response. The study of Stroth et al. (2009) compared performance of 35 adolescents (aged 13-14) on the Go/no go version of the Eriksen Flanker Task after 15 minutes of stationary biking at moderate intensity with performance after watching a video. They did not find an effect of the acute physical activity intervention on performance at the Go/ no go task. Findings of Audiffren, Tomporowski, & Zagrodnik (2009) indicated that 35 minutes of ergometer cycling had no effect on inhibiting and updating processes as measured with the Random Number Generation task after 2, 15 and 30 minutes following the intervention in 16 participants with an average age of 21. The interpretation of the results is limited because of the small sample size. Lambourne, Audiffren, & Tomporowski (2010) used the same exercise protocol as Audiffren et al. (2009) and failed to find an effect of 35 minutes of ergometer cycling on performance on the modified Paced Auditory Serial Attention task (PASAT) in 19 individuals with an average age of 21. However, this study also has a small sample size and therefore requires careful interpretation. Besides that, as the authors suggest, the failure to observe improved performance on the PASAT may be due to ceiling effects. The performances of the participants who are in their late adolescence were already high, leaving little room for improvement.

In most studies tests of executive functioning were administered immediately (within a few minutes) after physical activity had ceased. However, both Pontifex et al. (2009) and Cooper et al. (2012) did find an effect of acute physical activity on the Sternberg working memory task, measured respectively 30 minutes and 45 minutes after physical activity ended.

*3.1.1 Specification of the acute physical activity conditions in terms of type of physical acti*vity

Beneficial effects on executive functioning are identified for a wide range of acute physical activity interventions including treadmill walking, stationary biking, group games, yoga, exergaming, running and aerobic circuit training.

Six of the sixteen studies examined the differential effects of qualitatively unique types of acute physical activity on measurements of executive functioning. Pesce, Crova, Cereatti, Casella, & Bellucci (2009) investigated the differential effects of aerobic circuit training and team games both of moderate intensity (with slightly different average heart rate) on memory storage in 52 students aged 11-12 years (randomly selected from four classes). Team games are characterized by higher cognitive and social demands. They found that delayed recall scores (after 12 minutes) in the recency part were higher after both team games and aerobic training. During the delay period children could not rehearse because they had to participate in a classroom discussion. Pesce et al. review that a filled delay worsens the recall of recency items, instead of primacy items. The fact that the delayed scores in the recency part were higher after both physical activity interventions indicates that physical activity decreases the need for rehearsal and therefore shortens the consolidation time. However, immediate recall scores in both primacy and regency regions of a word list were only higher following team games. The study controlled for potential learning effects by using different word lists during each session and by counterbalancing the sequential order of the experimental sessions. The baseline session (not preceded by exercise) was the second session for all classes and the group games and circuit training session either being the first or third session. These findings are in line with the findings of Pirrie & Lodewyk who failed to find an effect of acute aerobic exercise on a simultaneous processing task that measured immediate recall.

The work of Budde, Voelcker-Rehage et al. (2008) showed that a higher improvement in selective attention scores of 115 adolescents aged 13-16 years was observed after a 10-minute coordinative exercise period than following a 10- minute bout of non-coordinative exercise (a normal sports lesson). Both interventions were of moderate aerobic intensity and average heart rate was the same for both interventions. The coordinative exercise condition was cognitively challenging and involved a series of bimanual coordination tasks, whereas the non-coordinative exercise condition comprised only repetitive motor movement. However, this study had a pilot character and it has no group that before both the pre and post-test was inactive. Therefore no conclusions can be drawn from this study about the general effect of acute physical activity on executive functioning, but only comparisons between coordinative and non-coordinative exercise can be made.

Inconsistent results exist regarding exergame interventions. O'Leary et al. (2011) observed a decrease in RT interference on a modified Eriksen Flanker Task after 20 minutes of treadmill walking compared to both seated rest and seated videogame in 36 participants (average age 21,2). Even though exercise intensities were the same (60% of maximum heart rate) no such effect was observed after exergame play. A later study of Best (2012) did report beneficial effects of exergame play on executive functioning. These contradictory results may be due to different intensity levels. Whereas O'Leary assessed the effect of low intense exergaming, Best used exergames of vigorous intensity. Best (2012) examined the effects of physical activity (PA) and cognitive engagement (CE) inherent in a videogame on executive functioning among 33 6-10 year- old children. Children's performance on a modified Eriksen Flanker test was assessed after they watched an age-appropriate video (low CE, low PA), after they played a sedentary video game (high CE, low PA), after they played an exergame (low CE, high PA) and after they played mini-exergames each requiring adaptive play (high CE, high PA). The amount of cognitive engagement inherent in an intervention had no effect on task performance, whereas physically active video game play (exergaming) enhanced performance on an inhibitory control task. The order of the four experimental conditions was counterbalanced enhancing the interpretability of the observed results. However, testing environments differed for the participants, it being either a quiet unused classroom (n=22) or a laboratory on the university campus (n=11). The cognitive measurements were not performed immediately after the end of the exergame. First heart rate monitoring equipment was removed, then the participants were given a two- minute break to drink water and to choose a small prize from a prize box.

Findings of Pontifex et al. (2009) indicate shorter reaction times at the Sternberg working memory task for 21 undergraduate students (average age 20) immediately and 30 minutes following acute aerobic exercise but not following resistance exercise or seated rest. With a greater reduction in reaction times for tasks that require greater involvement of working memory. However, careful interpretation is needed because of the small sample size and because of the fact that the intensity level of the different physical activity types differed.

Gothe et al. (in press) demonstrated that performance (i.e., shorter reaction times, increased accuracy) of 13 female college-aged participants on both inhibition and working memory tasks was better after an acute bout of yoga exercise compared to aerobic and baseline conditions. With the aerobic and baseline conditions not been significantly different. However, this study has a small sample size and therefore the results of this study need to be carefully interpreted.

It should be noted that three of the five studies that failed to find an effect of acute aerobic physical activity on executive functioning used ergometer cycling or stationary biking as physical activity intervention. However, Ellemberg & St-Louis-Deschênes (2010) did find an effect of stationary biking on performance on a choice response task.

3.1.2 Specification of the acute physical activity conditions in terms of duration

The duration of the acute physical activity interventions varied from 10 minutes (Cooper et al., 2012; Budde et al., 2008) to 42 minutes (Pesce et al., 2009). None of the sixteen studies systematically varied the duration of the acute physical activity to study the differential effect of physical activity interventions of different lengths. No obvious cross-sectional effect can be detected when considering the observed pattern of results. Of the studies that failed to find an effect of an acute bout of physical activity on executive functioning the duration level varied from 15 minutes to 35 minutes. The lengths of these studies are the same as the lengths of the studies that did find an effect of acute physical activity on executive functioning.

3.1.3 Specification of the acute physical activity conditions in terms of intensity

The studies included in this review reported intensity level in different ways, naming average heart rate , % of maximum heart rate or % of ventilatory threshold. To make comparisons between the studies intensity level of all studies is reported in % of maximum heart rate (by using the formula: ‘maximum heart rate=220-age’ or by using the maximum heart rate of the participants as reported) and identified as either low, moderate or vigorous, following the guidelines of the Physical Activity Resource Centre (2003). Among the acute intervention studies intensity level differed enormously, from low intensity yoga interventions (Gothe et al., in press) to vigorous physical education lessons (Pirrie & Lodewyk, 2012). None of the sixteen studies systematically varied the intensity of the acute physical activity interventions to study the differential effects of physical activity interventions of different intensity levels. Low- (5 studies), moderate- (4 studies) and vigorous (4 studies) intensity interventions enhanced executive functioning. In addition intensity level of studies that failed to find an effect of physical activity on executive functioning varied from low (2 studies) to moderate (2 studies) to vigorous (1 study) intensity. Thus, from this observed pattern results no conclusions can be drawn about the intensity level needed to elicit beneficial effects in executive functioning.

Table 1

Summary of findings of experimental studies on the effect of acute physical activity on executive functioning in children and adolescents.

Author	Age	N	Design	Physical activity type/ format	Duration of the intervention	Intensity Level of the intervention	Measurement EF	Sustainability (test after)	Conclusion	Limitations
Hillman et al. (2009)	Average 9,5 ±0,5	20	WS	Treadmill walking	20 min	60 % of estimated maximum heart rate (low intensity)	-Modified Erikson Flanker test (inhibitory control) -Achievement tests related to reading, spelling and mathematics	Testing once heart rate returned to within 10 % of pre-exercise levels	-Following treadmill walking increased response accuracy during incongruent trials relative to rest (p=0,008) (no sign effect on reaction time) -Better performance for reading comprehension relative to rest (p=0,016) .	-Small sample size -Time between end of physical activity and begin testing differs between subjects
Ellemberg & St-Louis-Deschênes (2010)	7- and 10 year old boys	72(36 per age group)	BS	Stationary biking while watching TV	30 min (plus a 5 min warming up and 5 min cooling down)	For 30 min 63 % of maximum heart rate (134 and 132 for the 7 – and 10 years old respectively) (low intensity)	Choice response time task (flexibility and inhibition)	immediately after the intervention	-After exercise children were sign faster on the choice response time tasks compared to children in the control group (p<0,05). -Activity had an equal effect on both age groups.	-No specification of time elapsed between end of physical activity and begin of cognitive testing
Pesce et al. (2009)	11-12	60	WS	Group games or aerobic circuit training	Average 38 min for circuit training and 42 min for team games	Aerobic circuit training: HR=146 BPM (70 % of maximum heart rate) Team games: HR= 137 BPM (65 % of maximum heart rate)	20 item word list learning task: immediate and delayed recall (memory storage processes)	immediately after the interventions	-Immediate recall sign benefitted from exercise (p<0,001; □^{2}=0,46). Immediate recall scores in both primacy (p=0,019) and regency (p<0,001) regions were higher following team games compared to baseline. -Delayed recall also sign benefitted from exercise (p<0,001; □^{2}=0,13). Delayed recall scores in the recency portion were	-No specification of time elapsed between end of physical activity and begin of cognitive testing

						(both moderate intensity)			higher after both team games (p=0,003) and circuit training (p=0,001) compared to baseline.	
Budde et al. (2008)	13-16	115	BS	Coordinative Exercise; Normal Sport Lesson	10 min	both: HR= 122 (59,4 % of maximum heart rate; low intensity)	D2 Test of Attention (selective attention)	immediately after the interventions	-Both coordinative exercise and a normal sport lesson enhanced performance on d2 task form pre to post test sign compared to baseline (p's<0,001). -A sign higher increase in performance was observed for the coordinative exercise group (p<0,01).	-No specification of time elapsed between end of physical activity and begin of cognitive testing -No control of potential learning effects, not counterbalancing the sequential order of the conditions -No control group that before both the pre and post-test was inactive
Tomporowski et al (2008)	7-11 (sedentary and overweight)	69	WS	Treadmill walking	15 min (plus 4 min warming up and 4 min cooling down)	15 min-3mph (=4,83 km/uur) (intensity level ?)	Visual Switching task	following (within 1 to 3 min) intervention	-No sign influence on children's global switch costs or error rates.	-Participants are sedentary and overweight -No specification of intensity level
Pirrie & Lodewyk (2012)	fourth grade students(mean age 9,75)	40	WS	Physical education lesson from the Heart Smart lesson by Activ8	20 min of moderate-to-vigorous physical activity within a 45 min lesson	20 min 65%-90% of maximum heart rate (moderate to vigorous intensity)	The Cognitive Assessment System (planning-trail making test, attention, simultaneous processing and successive processing)	Between 10 min and 1 hour following intervention	-Performance on the planning test sign benefitted from physical activity (p<0,001). -No improvement was detected for attention, simultaneous processing or successive processing.	-Wide range of intensity levels that have been achieved -No differentiation between participants that performed the cognitive testing after different amounts of time - Cognitive tests were not counter-balanced and therefore planning ability was always conducted first -Retesting was a confounder of the results
Gothe et al. (2012)	Average 20 (femal	30	WS	Yoga exercise session; aerobic exercise (treadmill	Both 20 min	Yoga: average heart rate = 77,5 (38,75 % of maximum heart	Modified Erikson Flanker task (inhibitory control). N-	immediately (within 5 min) following	-At the Flanker task and N-back task respectively response accuracy was sign higher after yoga compared to aerobic	-Only females included -May be yoga has resulted in motiva-tional and attentional enhancements

	es)			walking)		rate; low intensity) Aerobic exercise: 60-70% of maximum heart rate- average heart rate 154 (low to moderate intensity)	back task (working memory).	interventions	exercise (p<0,001; p=0,003)) and baseline (p<0,016; p=0,02). -At the N-back task RT's were shorter after yoga compared to aerobic (p<0,025) and baseline (p<0,01). -The aerobic and baseline were not significantly different.	because of the novelty and instruct-tion during the yoga session and the mind-body nature. -Yoga may improve more general attentional abilities
Pontifex et al. (2009)	20	21	WS	-Aerobic exercise(treadmillwalking) -Resistance exercise	Both 30 min	Aerobic: 84% of maximum heart rate (HR=162) (vigorous intensity) Resistance: 63% of maximum heart rate (HR=123) (low intensity)	Modified Sternberg task (working memory demands)	immediately after the intervention and 30 min after the intervention	-Shorter RT immediately and 30 min after acute aerobic exercise relative baseline (p<0,001; η^2=0,73) (no effect on response accuracy). -No sign effects after resistance exercise or seated rest.. -In tasks requiring increased working memory capacity RT benefitted the most.	-No specification of the term 'im-mediately'. -Small sample size -Intensity level of the different phy-scial activity types differed
Audiffren et al. (2009)	18-25	16	WS	Ergometer cycling exercise	35 min cycling (plus 5 min sitting without exercising and 5 min warming up)	35 min at 90%of the participant's ventilatory threshold (mean HR≈125) Maximum heart rate of female participants=182 and of males=186 (females: 69% of maximum heart rate; males: 67% of maximum heart rate) (moderate intensity)	Random Number Generation task (inhibiting and updating processes)	post exercise test at 2, 15 and 30 min following exercise termination.	-No sign influence on RNG performance after the cycling terminated.	-Small sample size
Lambourne et al. (2010)	Average 21	19	WS	Ergometer cycling exercise	35 min cycling (plus 5 min warming up)	35 min at 90%of the participant's ventilatory threshold (mean HR=143) Maximum heart rate of	Modified Paced Auditory Serial Addition Task (PASAT)	post exercise test at 1, 15 and 30 min following exercise termination.	-No sign influence on PASAT scores during or after exercise.	-Small sample size

						female participants=173,8 and of males=191 (females: 82% of maximum heart rate; males: 75% of maximum heart rate) (vigorous intensity)				
Best (2012)	6-10	33	WS; 2x2 design (PA:high, low) (CE:high, low) .	video; sendentary video game; exergame; mini-exergames	All 23 min including a water break at the halfway point	Video; HR=93 (44 % of maximum heart rate) (low intensity), sedentary video game; HR=94 (44 % of maximum heart rate) (low intensity), Exergame; HR=155 (73 % of maximum heart rate) (moderate intensity), MiniExergames; HR=160 (76 % of maximum heart rate) (vigorous intensity)	Modified Erikson Flanker task (inhibitory control).	Measured after each activity.	-Cognitive engagement had no sign effect task performance. -Physical activity in form of exergaming improved children's ability to resolve more quickly interference from conflicting visuospatial stimuli ($p<0,01$; □²=0,10). -A combination of PA and CE had no greater effect than PA alone.	-No specification of time elapsed between end of physical activity and begin of cognitive testing -Testing environment differed for the participants; quiet classroom (n=22) or laboratory on university campus (n=11)
Cooper et al. (2012)	averag e 13,2	45	WS	Modified version of the Multi Stage Fitness Test (10 repetitions of 7 x 20 m shuttle runs at 8,0km/h, with 30 s rest between each repetition)	10 min	HR=172 (when heart rate reached the threshold of 190 pp continued to walk with heart rate of 151; whilst running average heart rate was 178) (86 % of maximum heart	Stroop test (executive control/selective attention) and Modified Sternberg task (working memory demands)	45 min following exercise	-No sign effect on Stroop test performance. -On the Sternberg task, across all tasks, response times across the morning following exercise improved compared to resting (p=0,010) after which they slowed. No sign differences in response accuracy.	-No immediate exercise effects were assessed. -Probably the failure to of exercise effect on the Stroop test was related to test sensitivity (for reading only there also was no exercise effect)

						rate) (vigorous intensity)				
Tine & Butler (2012)	10-13 (lower and higher income)	164	BS	Running around an indoor track	12min	70-80% of maximum heart rate (vigorous intensity)	D2 Test of Attention (selective attention)	one minute after intervention	-Improved selective attention for of both lower and higher income children after running intervention (p<0,001; p²=0,768) with no sign improvement for the control group. -The improvement for lower income children was greater than for higher income children (p<0,001; p²=0,11).	-Participants were defined as higher or lower income in a dichotomous manner (family household income above $41,384 or below $29,055) -No income difference on pretest
Stroth et al. (2009)	13-14	35	WS	Stationary biking while watching tv	20 min	60% of maximum heart rate (low intensity)	Go/no go version of Eriksen Flanker Task (inhibitory control)	-	No effect of biking on performance on go/no go task compared to watching a video in rest.	-No specification of time elapsed between end of physical activity and begin of cognitive testing
Sibley & Beilock (2007)	Average 21,5	48	WS	Treadmill walking	30 min	74-76% of maximum heart rate (vigorous intensity)	Operation Span (OSPAN) and Reading Span (RSPAN) (working memory)	-	-Individuals with the lowest working memory at baseline (i.e., low quartile group) increased their working memory sign from the baseline to exercise session, (p < .01; d = 1.22). Individuals in the other three quartiles did not sign improve their working memory scores.	-No specification of time elapsed between end of physical activity and begin of cognitive testing
O'Leary et al. (2011)	Average 21,2	36	WS	Seated rest, seated videogame play, treadmill walking and exergame-based aerobic exercise (Wii Fit)	20 min	60% of maximum heart rate (low intensity)	Modified Eriksen Flanker Task (inhibitory control)	Testing once heart rate returned to within 10 % of pre-exercise levels	- RT interference decreased for treadmill walking as compared to both seated rest and seated videogame play (p < .05). No such effect for exergame play.	- Time between end of physical activity and begin testing differs between subjects

3.2 Chronic or long-term physical activity interventions

Nine studies examined the effect of chronic or long-term physical activity interventions on executive functioning in children and adolescents. All of these studies did find an effect of long-term physical activity on measurements of executive functions.

Hansen, Johnsen, Sollers, Stenvik, & Thayer (2004) examined the effect of training and detraining on a Continuous Performance test and a 2back task (working memory test) in 37 male sailors aged 18-22 years old. A pre-test was conducted following a three hour aerobic exercise program for eight weeks and a post-test was conducted for a trained group (a group that continued the same exercise program for four weeks) and a detrained group (a group that withdrew from the training program for four weeks). No significant differences were observed between the two groups at the pre-test, but at the post-test the trained group had faster reaction times and significantly more true positive responses on both tests of executive functioning compared to the pre-test. However, no control group that was inactive both before the pre- and post-test was included. Moreover, sample size was relatively small and the researchers did not control for practice effects both limiting the generalizability of the results. Kamijo et al. (2011) showed that a two hour after school physical activity program consisting of at least 70 minutes of moderate to vigorous physical activity for nine months improved performance on a Sternberg task in 43 preadolescent children (7-9 years old) compared to a waitlist control group. The observed beneficial effects were even greater for tasks that required a greater amount of working memory, though this was not the case in the largest- set size (the five-letter condition). It may be that this condition was too difficult for the preadolescent children.

Flynn (2012) showed that in 110 10-16 year old children a long term physically active video game play (or exergame) group (30 minutes weekly for 4 weeks) as well as a sedentary video group had a significantly better performance on Design Fluency and Trail Making tasks compared to a non-playing control group. There were no significant differences between the exergame and sedentary video game group. However, the Wii Fit group did significantly better from pre- to post-test, whereas for the sedentary video game group and the control group no significant differences from pre- to post-test were observed. This study was not described very extensively because it was used to obtain preliminary data for a dissertation research.

None of the long term physical activity studies specified the precise amount of time that had passed between the ending of the physical activity and the measurement of executive functioning. Most studies just state that measurement of executive functioning took place both before and ‘after’ or ‘following’ the physical activity intervention.

*3.2.1 Specification of the chronic physical activity conditions in terms of type of physical acti*vity

Beneficial effects on executive functioning are identified for a range of chronic physical activity interventions including exergaming, aerobic exercise programs, running and soccer.

Two out of nine studies examined the differential effects of qualitatively unique types of long-term physical activity on measurements of executive functioning. Tuckman & Hinkle (1986) showed that participation in a running intervention program (three 30-minute sessions a week for 12 weeks) yielded a higher capacity for divergent thinking in one 154 fourth-, fifth- and sixth graders, compared to the controls who engaged in normal physical education classes. However, intensity of each intervention was not specified. Therefore, it cannot be concluded that it was the difference in type of the physical activity intervention that accounted for this pattern of results. Findings of Staiano, Abraham, & Calvert (2012) indicate that a 10-week *competitive* exergame play intervention enhanced performance on Design Fluency and Trail Making tasks more than a *cooperative* exergame play intervention or a non-play control group in low-income and obese adolescents (aged 15-19 years). With no significant difference observed between the cooperative exergame condition and the non-play control group, indicating that competition is a key factor in mediating the effect of exergames on executive functioning. However, again intensity level of the interventions was not specified. In addition, only in the competitive group there was a significant positive correlation between weight loss and improvement in executive functioning skills.

3.2.2 Specification of the chronic physical activity conditions in terms of duration

Although all the chronic physical activity interventions comprise more than a single bout of physical activity, duration of the long-term physical activity interventions varied from 4 weeks (Flynn, 2012) to 9 months (Castelli, Hillman, Hirsch, Hirsch, & Drollette, 2011; Kamijo et al., 2011). Since all the long-term physical activity studies yielded positive effects of physical activity on executive functioning no conclusions about the exact duration needed to achieve a beneficial effect can be drawn.

Two of the nine studies systematically varied the length of the chronic physical activity intervention. Davis et al. (2007) found a significant effect of an aerobic exercise program on planning ability in 94 7-11 year old sedentary overweight children only for a high dose intervention (40 minutes per day five days a week for 15 weeks) and not following a low dose (20 minutes per day five days a week for 15 weeks) intervention. On the contrary Davis et al. (2011) did find a beneficial effect of both the low dose (20 minutes a day five days a week for 13 weeks) and the high dose (40 minutes a day five days a week for 13 weeks) interventions on planning scores in 171 7-11 year old sedentary and overweight children. But there was a dose response benefit of exercise on planning ability. Planning ability of children in the high dose group benefitted most from the physical activity interventions. The time between pre-test (baseline) and post-test was the same for all experimental conditions which increases the reliability of the results. However, it has to be taken into account that the participants were overweight and it is plausible that overweight and inactive children experience exercise differently than their fitter peers do.

3.2.3 Specification of the chronic physical activity conditions in terms of intensity

The studies included in this review reported intensity level in different ways, naming average heart rate or % of maximum heart rate. To make comparisons between the studies intensity level of all studies is reported in % of maximum heart rate (by using the formula: 'maximum heart rate=220-age') and identified as either low, moderate of vigorous following the guidelines of the Physical Activity Resource Centre (2003). Among the chronic intervention studies intensity level differed much less than among the acute intervention studies. Most studies reported a moderate to vigorous intensity level. Indicating that a certain level of intensity is needed to elicit physiological responses necessary to enhance executive functioning. However, four studies did not specify the intensity level of the long term physical activity intervention.

Castelli et al. (2011) investigated the effects of a FIT (Fitness Improves Thinking) kids program consisting of 120 minutes each school day for 9 months on the Stroop task and Comprehensive Trail Making Task in 59 schoolchildren (average age 8,8). Results show that 53% of the 120 minutes the children engaged in moderate physical activity and 11% of the time the children engaged in vigorous physical activity. Findings of this study indicate that time spent *in* target heart zone (55-80%) was not associated with performance on the executive functioning tasks. However, time spent *above* target heart zone, or vigorous physical activity was associated with improved performance on the executive functioning tasks. A limitation of this study is the fact that data for the control group were reported elsewhere and that therefore no direct comparisons with the control group could be made.

Only one long-term physical activity intervention study systematically varied the intensity level of the exercise program. Chang, Tsai, Chen, & Hung (2013) showed that a low intensity (40-50% of maximal heart rate) and moderate intensity (60-70% of maximal heart rate) soccer program intervention (coordinative exercise) benefitted inhibitory control as measured with the Eriksen Flanker test equally in 26 6-7,5 year old children. A limitation of this study is the lack of a control group that did not engage in any physical activity before administering all three executive functioning tasks. In addition the conditions (rest versus soccer) were not counterbalanced and therefore potential learning effects may confound the results.

Table 2

Summary of findings of experimental studies on the effect of chronic physical activity on executive functioning in children and adolescents.

Author	Age	N	Design	Physical activity type/ format	Duration of the intervention	Intensity Level of the intervention	Measurement EF	Sustainability (test after)	Conclusion	Limitations
Flynn (2012)	10-16	110	BS	Wii Fit intervention	30 min weekly for 4 weeks	-	Delis-Kaplan Executive Function System; Design Fluency and Trail Making (planning)	following the intervention	-Both the Wii Fit group and the sedentary video game group did better than the non-playing control ($p<0,05$). -No sign differences between Wii Fit and sedentary video game. - Wii Fit group did significantly better from pre to post-test ($p<0,001$) with no such effect for the other two conditions.	-No specification of time elapsed between end of physical activity and begin of cognitive testing -No specification of intensity level -Study used to obtain preliminary data for a dissertation research
Staiano et al (2012)	15-19 (overweight and obese)	54	BS	Exergame trainin intervention; competitive versus cooperative	30 min with average of 1 session per week for 10 weeks	-	Design Fluency and Trail Making test.	immediately after 10 weeks of training.	-The scores on both tests in the competitive condition increased sign more than the scores of in cooperative condition ($p=0,020$; $\square^2= 0,147$) and the scores in the no-play control group ($p=0,018$; $\square^2=0,149$) . -No sign improvement of scores in the cooperative condition and control group with the cooperative condition and control not been sign different.	-No specification of time elapsed between end of physical activity and begin of cognitive testing - Participants are overweight and obese -No specification of intensity level, may be differs between exercise conditions
Castelli et al. (2011)	Average 8,8	59	WS	FIT kids after school program (Fitness Improves Thinking)	120 min after every school day for 9 months	53% of the 120 min moderate physical activity, 11% vigorous physical activity	Stroop Color Word Test; Comprehensive Trail Making Test (planning)	following intervention	-Time spent above target heart zone (vigorous physical activity) sign predicted improvement in the Stroop task ($p=0,02$) and Trail making B ($p<0,001$).	-No specification of time elapsed between end of physical activity and begin of cognitive testing -Data control group reported elsewhere

Chang et al. (2013)	6-7,5	26	WS	Soccer exercise program (coordinative exercise)	35 min per session, twice a week for 8 weeks	Low intensity group: 40-50% of maximal heart rate (average heart rate 104). Moderate intensity group: 60-70% of maximal heart rate (average heart rate 140).	Modified Erikson Flanker task (inhibitory control).	following soccer intervention.	-The coordinative exercise intervention resulted in shorter reaction times and higher response accuracy (p's<0,001) in both congruent and incongruent trials. -The incongruent trials benefitted the most. -No sign difference between low and moderate intensity groups.	-No specification of time elapsed between end of physical activity and begin of cognitive testing -Small sample size -The conditions (rest versus soccer) were not counterbalanced -No control group that was inactive before all measurements
Davis et al. (2007)	7-11 (sedentary overweight)	94	BS	Aerobic exercise program (including running games, tag games, jump rope and modified basketball or soccer)	Low dose: 20 min /day High dose: 40 min/day Both 5 days per week for 15 weeks	Equal intensity for low and high dose groups. Average heart rate 166 BPM. (79 % of maximum heart rate) (vigorous intensity)	The Cognitive Assessment System (planning, attention, simultaneous processing and successive processing)	following the intervention.	-A sign effect of exercise on planning abilities was observed between the no-exercise control and the high-dose exercise conditions (p=0,01). -The control group and the low-dose exercise group were not sign different.	-No specification of time elapsed between end of physical activity and begin of cognitive testing - Participants are sedentary and overweight
Davis et al. (2011)	7-11 year (sedentary and overweight)	171	BS	Aerobic exercise program (including running games, tag games, jump rope and modified basketball or soccer)	Low dose: 20 min /day High dose: 40 min/day Both 5 days per week for 13 weeks	Equal intensity for low and high dose groups. Average heart rate 166 BPM. (79 % of maximum heart rate) (vigorous intensity)	The Cognitive Assessment System (planning, attention, simultaneous processing and successive processing)	following the intervention.	-Both low and high dose exercise resulted in higher planning scores (p=0,03) but not in higher mathematic achievement comparing to the control group. -There was a dose response benefit of exercise on planning scores and mathematic achievement (p=0,013).	-No specification of time elapsed between end of physical activity and begin of cognitive testing -Participants are sedentary and overweight
Tuckman	Fourth, fifth	154	BS	Running	three 30-min	-	Alternate Use	following	Running intervention increased the capacity	-No specification of time elapsed between

& Hinkle. (1986)	and sixth graders			program; normal physical education program (including a. o. volleyball, basketball (control)	running sessions per week for 12 weeks; regular PE lessons three times (sitxth graders) five times a week (fourth and fifth graders)		Test (divergent thinking)	intervention.	for divergent thinking comparing to the control (p<0,001).	end of physical activity and begin of cognitive testing -No specification of intensity level
Kamijo et al. (2011)	7-9	43	BS	Afterschool physical activity program	2 hour period following 150 school days - 9 month	At least 70 min of moderate to vigorous physical activity	Modified Sternberg task (working memory demands)	following intervention.	-The intervention group had greater response accuracy at post-test on Sternberg task (p=0,002; Cohen's d=0,73) -No such difference was observed for the waitlist group). -Tasks requiring greater working memory demands benefitted the most.	-No specification of time elapsed between end of physical activity and begin of cognitive testing -No exact specification of intensity level
Hansen (2004)	18-22 (male sailors)	37	BS	Aerobic exercise program (trained group; TG)	3 hour per week for 4 weeks	-	Continuous Performance test, Working Memory Test (2back test)	After the 4 week intervention	-Faster reaction times and more true positive responses on tests of executive function were observed for the trained group at the post test compared to the pre-test (p<0,001). -No such effect for the detrained group.	-No specification of time elapsed between end of physical activity and begin of cognitive testing -Only males included

4. Discussion

4.1 Summary

Both acute and chronic physical activity interventions are shown to have beneficial effects on a wide range of executive functions.

Effects on the following aspects of executive functioning have been ascertained using *acute* physical activity interventions: flexibility and inhibition measured with a choice response task (Ellemberg, & St-Louis-Deschênes, 2010), memory storage processes measured with free recall of word lists (Pesce et al., 2009), planning ability measured with a Trail Making Test (Pirrie, & Lodewyk, 2012), inhibitory control measured with a modified Erikson Flanker test (Best, 2012; Hillman et al., 2009; Gothe et al., in press; O'Leary et al., 2011), working memory measured with the Sternberg task (Cooper et al., 2012; Pontifex et al, 2009), the N-back task (Gothe et al., in press) and with the Operation/ Reading Span task (Sibley & Beilock, 2007) and selective attention measured with the D2 test of Attention (Tine, & butler, 2012; Budde et al., 2008).

Effects of *chronic* physical activity on the following aspects of executive functioning have been ascertained: working memory measured with a modified Sternberg task (Kamijo et al., 2011) and measured with a N-back task (Hansen et al., 2004), planning measured with a Continuous Performance Task (Hansen et al., 2004) and measured with the (Comprehensive) Trail Making Test (Castelli et al., 2011; Davis et al., 2011; Davis et al., 2007; Staiano et al., 2012; Flynn, 2012), executive control measured with the Stroop Test (Castelli et al., 2011), divergent thinking measured with the Alternate Use test (Tuckman, & Hinkle, 1986), inhibitory control measured with a modified Erikson Flanker task (Chang et al., 2013) and improvements have been observed for Design Fluency tasks (Staiano et al., 2012; Flynn, 2012).

There are studies that failed to observe a relationship between acute physical activity and executive functioning, but no studies could be found that reported a negative relationship between physical activity and executive functioning. What is the value of these studies that failed to find an effect of acute physical activity on executive functioning? Four of the five studies that failed to observe a beneficial effect had a relative small sample size. The sample size among others determines the statistical power of a study. Power is defined by Hinkle, Wiersma, & Jurs (2003) as 'the probability of rejecting the null hypothesis when it is false ($1-\beta$)' (p.299). In practice a power of $\geq 0,80$ is sufficient. With the sample size of Lambourne et al. (2010) (n=19) only effects of $d \geq 0,7$ can be detected with 80% certainty when the level of significance is 0,05 (Hinkle et al, 2003: Table C.11). Audiffren et al. (2009) (n=16) only can detect effects of d≥0,75 with 80% certainty when the level of significance is 0,05 (Hinkle et al, 2003: Table C.11). Gothe et al. (in press) (n=30) can detect effects of d≥0,6 with 80% certainty when the level of significance is 0,05 (Hinkle et al, 2003: Table C.11). Stroth et al. (2009) used a slightly larger sample (n=35) and therefore were able to detect an effect of d=0,5 with 80% certainty when the level of significance is 0,05 (Hinkle et al, 2003: Table C.11). Cohen's d classification for effect size is: small=0,25; medium=0,50 and large=1,00 (Hinkle et al., 2003). So these studies were only able to detect medium to large differences in executive function skills between the experimental and control conditions. Because sample sizes were too small these studies were not able to detect small to medium effects of physical activity with 80% certainty. However, it is possible that smaller effects of the physical activity interventions used in these studies on executive functioning exist.

In sum, this review suggests that engaging in either a brief or long-term period of physical activity enhances executive functioning in children and adolescents. These findings are only partially in accordance with recent findings of Verburg et al. (2013). Verburg et al. (2013) were the first that provided quantitative estimations of effect sizes and therefore were able to report the magnitude of the effect of physical activity on executive functioning. Verburg et al. (2013) reviewed that acute physical activity interventions benefitted executive functioning in children, adolescents and young adults (d=0,52). On the contrary Verburg et al. showed that chronic physical activity interventions did not significantly benefit executive functioning (d=0,16). However, only five studies addressing the effects of chronic physical exercise were included in the review of Verburg et al. (2013) and therefore these results are limited in interpretability.

4.2 Specification of the conditions under which physical activity benefits executive functioning

4.2.1 Specification in terms of type of physical activity

From the studies included in this review it can be concluded that executive functions are affected differently by physical activity interventions with different cognitive and social interaction demands. Pesce et al. (2009) showed that this is the case for memory storage processing, whereby immediate recall scores only benefitted from team games (high in social and cognitive demands) and not from circuit training. Similar results were observed by Budde et al. (2008). They showed that selective attention scores benefitted more from coordinative exercise which is cognitively engaging than from non-coordinative exercise. The study of Staiano et al. (2012) showed that engaging in *competitive* exergames enhances executive functioning more than *cooperative* exergames. Competitive exergames rely more on the functioning of the frontal lobes because of the increased demands to mentalize the self and other participants in order to win the game (Decety, Jackson, Sommerville, Chaminade, & Meltzoff, 2004). Taking these results into account, the conclusion seems to be in line with the conclusion from the review of Best (2010): more complex or cognitively engaging types of exercise have more favourable effects on executive functioning than simpler or repetitive types of exercise do.

A hypothesis proposed by Budde et al. (2008) for this observed pattern of results is that more complex types of exercise require more complex motor movements which in turn require activation of neural circuitry associated with executive functioning (e.g. the prefrontal cortex). The involvement of the prefrontal cortex in producing complex movements is supported by findings of Roland (1993). He shows that in simple or repetitive activity blood flow increases in the somatosensory cortex, motor cortex and premotor cortex. When subjects perform a task that requires the coordination of movements in relation to a goal, for example use a finger to find a route through a maze, cerebral blood flow also increases in the prefrontal cortex. Thus, a possible underlying mechanism for the beneficial effect of complex exercise types is that the activation of the neural circuitry during complex exercise may lead to pre activation of parts of the brain which are responsible for executive functioning in subsequent cognitive tasks. In other words, complex exercise a sort of primes executive functioning, leading to better performance on tasks that tab into executive functions. Another possible underlying mechanism refers to the plasticity of the human brain (Pascual-Leone, Amedi, Fregni, & Merabet, 2005). Complex exercise may lead to the plastic reorganization or modulation of neural circuits comprising the prefrontal cortex and therefore enhances performance on tasks in which adequate prefrontal cortex functioning is required.

Best (2012) observed a pattern of contrary results and failed to find an effect of the amount of cognitive engagement in an intervention on executive functioning. This study indicates that not the CE component but only the PA component of exercise increases executive functioning. According to Best (2012) a possible explanation for this different pattern of results is that in the previous studies not the amount of cognitive engagement inherent in the intervention but rather the amount of social interaction was responsible for the more beneficial impact on executive functioning. Social interaction demands inherent in physical activity are for example assessing the mental states, or intentions, of your team players and opponents in order to anticipate in their behaviour. This ability is called ‘theory of mind’ and depends on executive functioning and adequate functioning of the prefrontal cortex

(Best, 2010). Although this explanation can also account for the results of Pesce et al. (2009) and Staiano et al. (2012) it fails to explain the results Budde et al. (2008). The cognitively engaging exercise in the study of Budde et al. comprised no specific social interaction. Examples of the cognitively engaging exercise used in this study are bouncing a volleyball alternating with the right or left hand or bouncing a volleyball with the hand and at the same time controlling a soccer ball with the foot. So, an alternative explanation for the observed results of Best (2012) is more adequate. In the study of Best (2012) only video games were used in contrast to the previous studies. Exergames are defined by Best (2012) as "new generation of videogames that stimulate a more active, whole-body gaming experience" (p.1502). The exergame condition designed to require no cognitive engagement was a game called "marathon", in which the child's virtual character is challenged to run as far as possible in 10 minutes. In order to move the virtual character most effectively the child had to continually monitor and adjust his or her position and jogging motion on the pressure-sensitive buttons of the response pad (Best, 2012). This monitoring and adjustment is probably more complex and relies more on executive control processes than was intended and therefore may also prime executive functioning needed for the subsequent modified flanker task. This unintentional cognitive engagement in the 'marathon' task can explain why 'the mini exergames', the exergame condition designed to require cognitive engagement, failed to result in a stronger effect on the executive functioning task.

So, when taking the studies into account that manipulated the physical activity intervention in terms of *type* there is evidence to state that executive functioning benefits most from physical activity interventions that are cognitively engaging. In addition, it seems that physical activity that requires social interaction also benefits executive functioning to a greater extent than physical activity demanding less social interaction. It is likely that physical activity interventions high in both cognitive and social interaction demands achieve the greatest beneficial effects on executive functioning. In coordinative physical activity that requires social interaction children and adolescents are even more cognitively engaged than in coordinative physical activity without social interaction demands, because assessing the mental states of others depends on executive functioning. Thus by physical activity which is both cognitively and socially engaging executive functioning would be impacted in more ways than one. Therefore children and adolescents should engage in cognitive challenging exercise preferably group games so that social interaction is needed and to maximize the effect on executive functioning a competitive element should be included.

Moreover, when considering the studies that failed to find an effect of physical activity on executive functioning it can be observed that all of these used interventions in which cognitive and social demands were low (e.g. treadmill walking or ergometer cycling). This might be the reason for the failure to observe any beneficial effect of the physical activity intervention on tasks that tab into executive functions.

4.2.2 Specification in terms of duration

Acute physical activity interventions are suitable for enhancing executive functioning. Thus, a single bout of physical activity is enough to increase performance on a range of executive functioning tasks. This observation is in line with the review of Barenberg (2012) and narrows the range of possible underlying neurobiological mechanisms that can explain the relationship between physical activity and executive functioning. Not the structural change in an individual's organism induced by extensive training programs over several weeks, but rather the physiological changes that normally accompany a one-time physical activity are the most obvious underlying mechanism (Barenberg, 2012). According to Barenberg et al. (2012) the most probable underlying neurobiological mechanism for these observed effect is the immediate release of brain neurotransmitters (especially dopamine) during a period of physical activity. However, underlying neurobiological mechanisms of the beneficial effect of physical activity on executive functioning remain to be explored in more detail.

None of the acute physical activity studies systematically varied the length of the intervention and only two chronic physical activity studies did so. These two studies both found a dose response benefit of exercise on executive functioning, with children in the high dose group (40 minutes per day) benefitting more than children in the low dose group (20 minutes per day) (Davis et al., 2007; Davis et al., 2011) .

Ergo, there is tentative evidence indicating that engaging in a longer period of physical activity each day benefits executive functioning to a greater extent. However, intervention effects are found at all duration levels from acute bouts of 10 minutes to 9 month training programs and therefore more research is needed to determine the exact length of a physical activity intervention needed to enhance executive functioning.

4.2.3 Specification in terms of intensity

Just one of the twenty five studies included in this review systematically varied the intensity of the physical activity interventions to study the differential effect of physical activity interventions of different intensity level. However, this study indicated that an intervention of moderate intensity not enhanced executive functioning more than an intervention of low intensity did. The study of Castelli et al. (2011), on the contrary, indicated that only time spent *above* target heart zone, or vigorous physical activity was associated with improved performance on the executive functioning tasks.

Most studies included in this review use interventions of moderate to vigorous intensity instead of low intensity. Indicating that a certain level of intensity is necessary to effectively alter executive functions. However, intervention effects are found at all intensity levels and therefore on base of the studies included in this review there is no conclusive evidence that intensity level of the physical activity determines the effect on executive functioning.

4.3 The sustainability of the beneficial effects of physical activity on executive function

In most studies, the subjects took the cognitive tests immediately after the physical activity ended. Five of the acute physical activity intervention studies and all of the chronic physical intervention studies, however, did not specify the exact time elapsed between the end of the exercise bout and the beginning of the cognitive assessments. Most of these studies just state that executive functioning is assessed 'following' the physical activity intervention. This lack of detail makes the interpretation of these terms very difficult. Some studies, for instance, use EEG techniques which require extensive preparation before the cognitive assessment can start. Taking this into account to what extent do the results of such studies reflect true *immediate* exercise effects?

Two studies did find an effect of an acute bout of physical activity on measurements of working memory after respectively 30 and 45 minutes (Pontifex et al., 2009; Cooper et al., 2012). Pirrie & Lodewyk (2010) did find an effect of acute physical activity on executive functioning when children were tested between 10 minutes and one hour after the physical activity intervention. The research design of Pirrie & Lodewyk (2010) had the potential to shed light on the sustainability question. They began cognitive testing 10 minutes after the end of the physical activity intervention with all students being tested within one hour of the end of the physical education class. The cognitive tests were administered in three rounds with seven students being tested in each sequential round. However, this study did not examine the differential performance on the cognitive tasks of these students in the different rounds. In addition to this, students were independently reading in the classroom, while waiting for their turn. This reading can be a confounder of the results.

All in all taking these studies on the effect of acute physical activity into account we can assume that the beneficial effects of acute physical activity on executive functioning may at least persist for half an hour.

Since all of the chronic interventions studies state that cognitive measurement took place ‘following’ the intervention no conclusions about the sustainability of these long term interventions can be drawn. My hypothesis that the physiological changes produced by long-term interventions are more structural and therefore chronic physical activity interventions have more permanent effects on executive functioning remains an unanswered question.

Further research that carefully measures executive functioning after different amounts of time is needed to draw conclusions about the sustainability of the beneficial effects of physical activity on executive functioning.

4.4 Limitations of this review and recommendations for further research

A limitation of this review is that not all studies specified the intensity level of the physical activity intervention nor did all studies specify the intensity level in the same way. This limits the amount of conclusions that can be drawn about the intensity level needed to achieve a beneficial effect. Important to take into consideration is the ecological validity of the studies used in this review. In some studies the physical activity intervention takes place in the laboratory whereas in other studies the intervention takes place at school. The studies that imply their physical activity intervention in a school setting may have a greater ecological validity. However, these applied studies have problems with confounders as the amount of social interaction inherent in the intervention or the variation in precise activity of each single child. Not all studies specified the time elapsed between the end of the physical activity intervention and the start of the cognitive assessment. Further studies should specify this to draw conclusions about the sustainability of the beneficial effects of physical activity on executive functioning.

Because this is a bachelor thesis and therefore limited in the amount of questions that can be answered, this review did not take into account the developmental aspect of executive functioning. However, separable executive functions follow different developmental pathways and mature at different rates. Therefore, it is likely that the effects of physical activity on executive functioning vary with age and stage of (brain) development. For example Guiney & Machado (2013) reviewed that in children especially working memory *capacity* and in young adults working memory *updating* has shown to benefit from physical activity. Findings of Verburg et al. (2013), meanwhile, did not indicate age related differences in the effect of physical activity on executive functioning. Of all studies included in this review only Ellemberg & St-Louis-Deschênes (2010) systematically studied the effect of an acute bout of physical activity on executive functioning per age group. They found in line with Verburg et al. (2013) that 30 minutes of stationary biking benefitted both 7 and 10 year old boys equally on a choice response time task. However, further research is needed to draw firm conclusions about the differential effects of physical activity on different age groups. It is important to explore the differential sensitivity of subpopulations in order to give an answer to the question which subpopulations are most worth targeting with psychical activity interventions.

I explored two other relevant questions for further research. First, findings of both Sibley & Beilock (2007) and Tine & Butler (2012) show that the effect of physical activity on executive functioning is not uniform across all individuals. Individuals with low baseline cognitive abilities are shown to benefit the most from physical activity interventions. The observation that children from lower-income families benefit more from an acute physical activity intervention than do children from higher-income families raises the need for more studies that systematically explore the differential sensitivity of children from higher- and lower income families, or more general higher- and lower SES children. Executive functions have shown to be worse in children with low SES possibly due to less cognitive stimulation and more early life stress leading to functional and anatomical brain differences (Noble, Norman, & Farah, 2005). Therefore, it seems possible that children from lower-income families could improve more if they have more room to improve. Second, little is known about the effect of postexercise affective responses on performance on cognitive tasks (Tomprowski et al. 2008). It is plausible that children who experience positive affect after a period of physical activity perform different on subsequent cognitive tasks. Tomporowski & Ganio (2006) show that young adults who experience positive affect after a physical activity intervention perceive cognitive demands of subsequent executive functioning tasks as less frustrating. A hypothesis therefore is that children and adolescents who experience positive affect after engaging in physical activity perform better on subsequent tasks that tap into executive functions. Further research should explore the effects of these postexercise affective responses and their effect on executive functions.

This review was the first that carefully explored under which conditions physical activity enhances executive functions in young healthy populations and its results are useful in designing physical activity interventions that are applicable to practical contexts in real life. To achieve a beneficial effect no chronic physical activity interventions are needed but a single acute bout of physical activity is enough. To achieve the greatest beneficial effects physical activity interventions have to be cognitively and socially engaging in order to prime or reorganize the neural circuitry necessary in subsequent executive functioning tasks. There is tentative evidence indicating that engaging in a longer period of physical activity each day benefits executive functioning to a greater extent. Most studies included in this review use interventions of moderate to vigorous intensity instead of low intensity, indicating that a certain level of intensity is necessary to effectively alter executive functions. However, intervention effects are found at several duration and intensity levels. Therefore still more research, manipulating the duration (light, moderate, vigorous) and intensity (e.g. 10 min, 30 min, 1 hour) of the physical activity, is needed to specify the exact duration and intensity level needed to achieve a beneficial effect on executive functioning.

In a society in which children and adolescents are becoming more sedentary and less fit and in which physical education lessons are cut from education programs, it is important to notice the beneficial effects of physical activity interventions on executive functions. Especially because executive functions are related to learning processes and therefore extremely relevant in academic achievement. This review shows that one can enhance executive functions and thus academic performance with the simple and inexpensive method of physical activity and therefore may persuade readers to implement physical activity in education programs at school.

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