Part A

Physical exercise and neurocognitive functioning

Chapter 2

Physical exercise and executive functions in preadolescent children, adolescents and young adults: A meta-analysis

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ABSTRACT

Purpose The goal of this meta-analysis was to aggregate available empirical studies on the effects of physical exercise on executive functions in preadolescent children (6–12 years of age), adolescents (13–17 years of age) and young adults (18–35 years of age).

Method The electronic databases PubMed, EMBASE and SPORTDiscus were searched for relevant studies reporting on the effects of physical exercise on executive functions. Nineteen studies were selected.

Results There was a significant overall effect of acute physical exercise on executive functions (d=0.52, 95% CI 0.29 to 0.76, p<.001). There were no significant differences between the three age groups (Q(2)=0.13, p=.94). Furthermore, no significant overall effect of chronic physical exercise (d=0.14, 95%CI −0.04 to 0.32, p=.19) on executive functions (Q (1)=5.08, p<.05) was found. Meta-analytic effect sizes were calculated for the effects of acute physical exercise on the domain's inhibition/interference control (d=0.46, 95% CI 0.33 to 0.60, p<.001) and working memory (d=0.05, 95% CI −0.51 to 0.61, p=.86) as well as for the effects of chronic physical exercise on planning (d=0.16, 95% CI 0.18 to 0.89, p=.18).

Conclusions Results suggest that acute physical exercise enhances executive functioning. The number of studies on chronic physical exercise is limited and it should be investigated whether chronic physical exercise shows effects on executive functions comparable to acute physical exercise. This is highly relevant in preadolescent children and adolescents, given the importance of well-developed executive functions for daily life functioning and the current increase in sedentary behavior in these age groups.

INTRODUCTION

Modern society is adapting to a sedentary lifestyle (Levine, 2010). This global trend is a major threat to public health (World Health Organization, 2001). Lower levels of physical exercise have been associated with an increased incidence of disabilities and diseases including hypertension, obesity and diabetes (Laaksonen, Lakka, Salonen, Niskanen, Rauramaa, & Lakka, 2002), while high levels of physical exercise are associated with, for example, higher musculoskeletal fitness and a lower risk of physical disability and diseases (Warburton, Nicol, & Bredin, 2006). However, the benefits of an active lifestyle are not restricted to physical health: higher levels of physical activity have been related to higher levels of cognitive performance as well. Cognitive functions are functions subserved by the central nervous system including a variety of functions such as memory and attention (Lojovich, 2010). Moreover, there is evidence for a causal relationship between physical exercise and improved cognitive functioning in older adults (Kamijo, Hayashi, Sakai, Yahiro, Tanaka, & Nishihira, 2007; Kramer, Hahn, McAuley et al., 2001; Tseng, Gau, & Lou, 2011). For instance, it has been shown that walking improved memory and attention in the sedentary elderly (Kramer et al., 2001; Kashihara, Maruyama, Murota, & Nakahara, 2009). Several mechanisms have been proposed that possibly mediate the positive effects of physical exercise on neurocognitive mechanisms (McAuley, Kramer, & Colcombe, 2004; Voss, Nagamatsu, Liu-Ambrose, & Kramer, 2011). Regarding the direct effects of physical exercise, the mean cerebral blood flow (CBF) is found to be elevated in the brain, which may relate to cognitive functioning (Chmura, Nazar, Kaciuba-Uscilko, 1994; Querido & Sheel, 2007). Furthermore, physical exercise around the lactate threshold leads to immediate increases in the plasma levels of catecholamines, adrenocorticotropic hormone, vasopressin and β-endorphin in the peripheral blood circulation (Anish, 2005; McMorris, Collard, Corbett, Dicks, & Swain, 2008; Dishman & O'Connor, 2009), which are thought to reflect increased neurotransmitter secretion in the central nervous system leading to elevated arousal, subsequently enhancing cognitive performance (Ding, Li, Zhou, Rafols, Clark, & Ding, 2006).

Concerning the effects of regular (long-term) physical exercise on cognitive functioning, physical exercise is found to enhance new blood vessel formation and extension in the brain (angiogenesis), which is thought to improve the perfusion capacity of the brain (Swain, Harris, Wiener et al., 2003). Furthermore, multiple neurostructural changes at the level of the synapse, dendrites and cell formation in response to physical exercise have been observed (neurogenesis). Additionally, multiple neurotrophic factors (eg, brain-derived neurotrophic factor, nerve growth factor, vascular endothelial growth factor, granulocyte colony-stimulating factor and insulin-like growth factor) have been found to be upregulated by physical exercise in humans. These neurotrophic factors play an important role in neural growth and neuron survival, thereby influencing learning and memory, processes that are critical for cognitive functioning (Colcombe & Kramer, 2003; McAuley et al., 2004; Ahn & Fedewa, 2011; Tomporowski, Lambourne, & Okumura, 2011). In line with the upregulation of neurotrophic factors, high physical fitness is associated with larger brain volumes. For example, children with higher cardiovascular fitness have larger volumes of the basal ganglia and hippocampus as compared to children with lower physical fitness levels (Chaddock, Erickson, Prakash et al., 2010). This evidence strongly suggests that exercise-induced neural plasticity is not merely restricted to areas of the brain serving motor function and may therefore translate into enhanced cognitive functioning.

In the literature, the terms acute exercise and chronic exercise are widely used to refer to investigations of effects of physical exercise. In studies of acute exercise, the activity consists of a single short-term exercise bout (typically spanning between 10 and 40 min), whereas in studies of chronic exercise, the activity consists of an exercise program of multiple training sessions per week for a longer period of time (typically spanning between 6 and 30 weeks).

Most studies on the effects of physical exercise focused on cognitive functioning in the elderly and on specific patient groups, including patients with dementia (Colcombe & Kramer, 2003; Kamijo et al., 2009). Recently, there is increasing interest in the effects of physical exercise on cognitive functioning in children and adolescents (Ahn & Fedewa, 2011; Tomorowski, Lambourne, & Okumura, 2011) and a few reviews emerged that concluded that higher levels of physical exercise are associated with better cognitive functioning, and with enhanced executive functioning in particular (Tomporowski, Davis, & Miller, 2008; Best, 2010; Biddle & Asare, 2011).

Executive functions are generally defined as ‘higher level cognitive processes’ that manage other more basic cognitive functions (e.g., visual-spatial perception) (Alvarez & Emory, 2006). Executive functions consist of functions such as planning, self-regulation, initiation and inhibition and cognitive flexibility (Kramer, Humphrey, & Larish, 1994; Pennington & Ozonoff, 1996). Both the frontal and subcortical brain regions subserve executive functions (Alvarez & Emory, 2006), although the prefrontal cortex is thought to play a key role (Anderson, 2002). Executive functions develop from early childhood through adolescence into adulthood (Zelaz, Craik & Booth, 2004; Blakemore & Choudhury, 2006), with large developmental changes during the elementary school years (Welsh, Friedman, & Spekers, 2006; Best, Miller, & Jones, 2009). The development of executive functions is paralleled by neuroanatomical changes in the prefrontal cortex, which are marked by decreases in grey matter and increases in white matter density between age 7 and young adulthood (Giedd, Blumenthal, & Jeffries, 1999; Sowell, Thompson, Leonard et al., 2004; Paus, 2005). Consequently, a commonly accepted explanation for the late development of executive functions is the relatively late maturation of the prefrontal cortex (Anderson, 2001).

The literature mainly investigated the association between physical fitness and cognitive functions or the academic achievement of preadolescent children (Castelli, Hillman, Buck et al., 2007; Kwak, Kremers, Bergman et al., 2007; Tomporowski et al. 2008; Chomitz, Slining, McGowan et al., 2009), and several studies also investigated the association between physical fitness and executive functions in preadolescent children and adolescents (Buck, Hillman, & Castelli, 2008; Hillman, Buck, Themanson et al., 2009; Chaddock et al., 2010). Few studies reported on the effects of chronic (long-term) physical exercise interventions on cognitive functioning, and executive functions in particular, in healthy groups of children or adolescents and young adults (Stroth, Hille, Spitzer et al., 2009; Fisher, Boyle, Paton et al., 2011; Kamijo, Pontifex, O’Leary et al, 2011). Most of the cross-sectional studies reported a positive relationship between high fitness levels and cognitive functioning.

Regarding randomized controlled studies (RCTs) investigating the effects of both acute and chronic physical exercise on executive functions, inconsistent results were found in the maturing brain. The recent reviews that addressed the relationship between physical exercise and executive functions in preadolescent children and adolescents did not include the literature on young adults (Tomporowski et al., 2008, Best, 2010; Biddle et al., 2011; Tomporowski et al., 2011). It therefore remains unknown whether physical exercise has beneficial effects on executive functions throughout the whole period of brain maturation. Moreover, none of these reviews has provided quantitative estimations of the effect sizes, leaving the exact magnitude of the effects of physical exercise on executive functions unknown.

The present meta-analysis is the first to report a systematic quantification of the effects of physical exercise on executive functions across the critical periods of brain maturation. First, the meta-analytic outcomes on the effects of acute and chronic physical exercise on executive functions in preadolescent children, adolescents and young adults will be addressed separately. Second, to examine whether specific executive functions profit to a similar extent from physical exercise, we investigated the effects of exercise on domains of executive functioning. Following Pennington and Ozonoff (1996) we thereby distinguished between the following executive functions: inhibition/interference control, working memory, set-shifting, cognitive flexibility, contextual memory and planning.

METHODS

This meta-analysis was performed according to the guideline provided by Stroup et al. (2000). This guideline provides checklists and gives instructions for presentation of meta-analytic results, such as detailed tables and summaries of study estimates and combined estimates.

STUDY SELECTION AND DESCRIPTION

This meta-analysis included studies that (1) examined the effects of physical exercise on executive functions in preadolescent children (6–12 years of age), adolescents (13–17 years of age) or young adults (18–35 years of age), (2) included groups of individuals with a mean age ≤30 years, because developmental changes in white and grey matter have been found up to about 30 years of age (Whitford, Rennie, Grieve et al., 2007; Lebel, Walker, Leemans et al., 2008; Westlye, Walhovd, Dale et al., 2010) and (3) examined either acute or chronic physical exercise.

The electronic databases PubMed (early 1800–2012), EMBASE (1974–2012) and SPORTDiscus (1830–2012) were searched for relevant studies. The search terms 'physical activity', 'physical exercise', 'training', 'aerobic exercise', 'executive functions', 'children', 'youth', 'adolescence', 'young adults' and equivalents were combined to locate studies, and reference lists of retrieved studies were searched to locate other relevant studies. The searches were limited to studies published in the English language and indexed in one of the databases before 1 April 2012. A flow diagram of identification, screening and the inclusion of selection of studies is shown in figure 1 (Moher, Liberati, Tetzlaff et al., 2009). If multiple studies were published using the same participants, only the study with the largest sample was included to prevent the use of correlated data that would inflate homogeneity (Davis, Tomporowski, Boyle et al., 2007; Tomporowski, Davis, Lambourne et al., 2008; Davis, Tomporowski, McDowell et al., 2011). A total of 20 articles was selected. Because 3 articles reported on more than one experiment, 25 studies were extracted for the meta-analysis (table 1). For three studies, no data were provided that allowed the calculation of effect sizes (Kamijo, Nishihira, Higashiura et al., 2007; Coles & Tomporowski, 2008; Sanabria, Morales, Lugue et al., 2011). Therefore, we contacted the authors by email to establish missing details in the results sections of the written reports.

STUDY QUALITY

The quality of included studies was assessed by two authors (LV and MK) independently according to the Newcastle-Ottawa Scale (Wells et al., 2000). Because not all items were applicable to crossover designs and RCTs without patient groups, (eg, quality of follow-up measurements), the scores ranged from 0 to 6 for crossover designs and from 0 to 7 for RCTs. The measure allows the quantification of study quality according to the selection of individuals (2 points), comparability of experimental and control groups (2 points) and exposure of individuals to the condition assessed (3 points). Consequently, higher quality studies receive higher scores (0–7 points). Inter-rater discrepancies were resolved by consensus.

STATISTICAL ANALYSES

Statistical analysis was performed using Comprehensive Meta-Analysis (CMA, Biostat, 2005) and SPSS software (Version 17.0, IBM, 2008). Effect sizes for all individual studies were calculated (Cohen's d) and weighted by the study inverse variance, thereby accounting for sample size and measurement error (Hedges, Olkin, & Statstiker, 1985). Subsequently, meta-analytic effect sizes were calculated using a fixed approach for homogeneously distributed effect size data (Cochran, 1954), whereas a random approach was used for heterogeneously distributed effect size data (Gliner, Morgan, & Harmon, 2003). Meta-analytic effect sizes were based on a minimum of two studies. Heterogeneity of the data for each meta-analytic effect size was assessed using Q-testing (DerSimonian & Laird, 1986; Egger, Smith, & Phillips, 1997), and it was investigated whether study quality was a moderator of effect sizes using meta-regression analysis. Positive effect sizes indicate better performance on tests of executive functions in the experimental condition as compared to the control condition. Cohen's guidelines for interpretation of effect sizes were applied, translating d=0.2 into small, d=0.5 into moderate and d=0.8 into large effect sizes (Cohen, 1988).

First, we determined the effects of acute (n=19) and chronic (n=5) physical exercise on executive functions across the three age groups and for the three age groups separately. Second, we calculated meta-analytic effect sizes to investigate the effects of physical exercise on specific executive function domains. Third, to investigate the effects of duration of the physical exercise interventions on executive functions, meta-regression was performed. Regression slopes were manually standardized by multiplying them with the ratio of the SD of the independent variable (duration of physical exercise) and the SD of the dependent variable (executive function outcome) (Luskin, 1991) and interpreted as correlation coefficients according to Cohen (1988).

The possibility of publication bias was assessed for all meta-analytic effect sizes using three complementary methods: (1) Rosenthal's fail-safe N was calculated to determine the necessary number of studies to nullify the overall effect (Rosenthal, 1995), (2) linear regression methods were applied to determine the degree of funnel plot asymmetry as proposed by Egger et al. (Egger, Smith, & Schneider, 1997), (3) the relation between sample size and effect sizes was assessed using meta-regression to reveal the possible tendency that significant

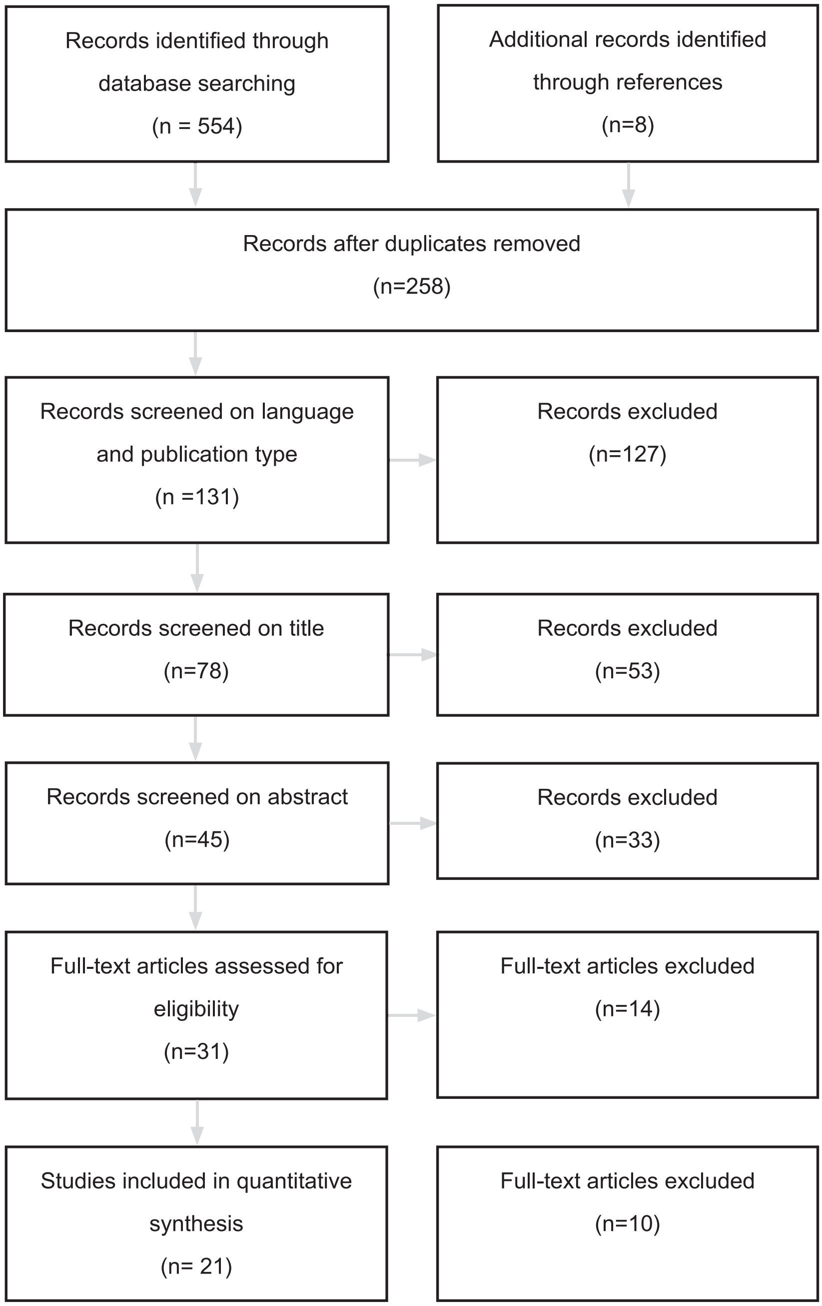

Figure 1. PRISMA flow diagram of study selection.

results in small samples are easier to publish than non-significant results, which would become evident by a significant positive association between sample size and effect size. Significance testing was two-sided. α-level was set at 0.05.

RESULTS

Table 1 displays the characteristics of the 24 studies (19 acute, 5 chronic) that were included in the meta-analysis and figure 2 displays the results of these studies. Meta-analytic results, heterogeneity statistics and results of publication bias analyses are shown in table 2. Nine studies were RCTs with a control group having seated rest on a couch or ergometer, instead of performing physical exercise. Fifteen studies employed a crossover design in which participants attended an exercise session as well as a rest or control session (seated rest on a couch or ergometer) in random order. Studies investigated the effects of physical exercise on inhibition/interference control (n=13), working memory (n=5), planning (n=4), set-shifting (n=1), and cognitive flexibility (n=1). There were no significant negative associations between study quality and effect sizes (standardized $\beta=0.11$, $p=.79$ and $\beta=-0.11$, $p=.44$) for studies on acute and chronic physical exercise, respectively).

EFFECTS OF ACUTE PHYSICAL EXERCISE ON EXECUTIVE FUNCTION DOMAINS

There were 19 studies investigating the effects of acute physical exercise on executive functions, of which two studies assessed preadolescent children, three studies assessed adolescents and 14 studies assessed young adults. Acute physical exercise had a moderate positive overall effect ($d=0.52$) on executive functions. Concerning age, a moderate positive effect was found in preadolescent children, adolescents and young adults ($d=0.57$, $d=0.52$ and $d=0.54$, respectively). The between group comparison for age-related effects was not significant ($Q(2)=0.04$, $p=.98$). Regarding specific domains, 12 studies reported on the effects of acute physical exercise on inhibition/interference control and showed a significant small-to-moderate positive effect size ($d=0.46$). More specifically, there was found a moderate positive effect on inhibition/interference control in the preadolescent group ($d=0.57$), a moderate effect in the adolescent group ($d=0.52$) and a small-to-moderate effect in the young adult group ($d=0.42$). The between-group comparison for age-related effects on inhibition/interference control was not significant ($Q(2)=0.13$, $p=.94$), indicating that acute physical exercise has similar effects on inhibition/interference control in the three age-groups. Four studies reported on the effects of acute physical exercise on working memory in only young adults. A meta-analysis of these studies showed a non-significant effect size (d=0.05). No indications for publication bias were found for both the meta-analytic effect size of acute physical exercise on executive functions as well as for the meta-analytic effect sizes of the effects of acute physical exercise on inhibition/interference control in all three age groups. Because the meta-analytic effect size on working memory was non-significant, no publication bias analyses were performed. The overall effect of acute physical exercise was heterogeneously distributed, indicating considerable differences in effect sizes among studies. The meta-analytic effect sizes of inhibition/interference control and working memory showed no heterogeneity, indicating minor differences in effect sizes between studies investigating specific domains (table 2).

EFFECTS OF CHRONIC PHYSICAL EXERCISE ON EXECUTIVE FUNCTION DOMAINS

Five studies reported on the effects of chronic physical exercise on executive functions. Across age groups, a meta-analysis of these studies showed a non-significant effect size (d=0.14). Four studies reporting on planning performance in only preadolescent children showed no significant effects of chronic physical exercise (d=0.16). For none of the meta-analytic results for the effects of chronic physical exercise was there any evidence of publication bias. The meta-analytic effect sizes showed no heterogeneity, indicating minor differences in effect sizes between studies (table 2).

META-REGRESSION ON THE EFFECTS OF DURATION OF PHYSICAL EXERCISE ON EXECUTIVE FUNCTIONS

Duration of physical exercise did not account for a significant proportion of the variance for both the effects of acute and chronic physical exercise on executive functions (standardized $\beta=-0.29$, p=.15 and $\beta=-0.39$, p=.35).

Table 1. Studies included for meta-analysis investigating the effects of physical exercise on executive functions

	Study	N	Mean Age	Gender (% male)	Type	Design	EF Domain	Exercise Duration (minutes)
Preadolescents	Ellemberg et al., 2010	75	9,1	100	Acute	RCT	Inhibition	20
	Kamijo et al., 2011	36	9	47	Chronic	RCT	Working Memory	21600
	Davis et al., 2007a	62	9,2	n/a	Chronic	RCT	Planning	1500
	Davis et al., 2007a	61	9,2	n/a	Chronic	RCT	Planning	3000
	Fisher et al., 2011	64	6.1	44.7	Chronic	RCT	Planning	1200
Adolescents	Stroth et al., 2009a	35	14,2	57	Acute	Crossover	Inhibition	20
	Stroth et al., 2009a	35	14,2	57	Acute	Crossover	Inhibition	20
	Budde et al., 2008	99	14,9	81	Acute	RCT	Inhibition	10
Young Adults	Audriffen et al., 2010	18	21.1	50	Acute	Crossover	Inhibition	35
	Tomporowski et al., 2006	22	21.6	55	Acute	RCT	Set-shifting	40
	Sibley et al., 2006	76	22,5	51	Acute	Crossover	Inhibition	20
	Chang et al., 2011	42	22.1	31	Acute	RCT	Planning	30
	Yanagisawa et al., 2010	20	21,5	85	Acute	Crossover	Inhibition	10
	Kamijo et al., 2007	12	25,7	100	Acute	Crossover	Inhibition	20
	O'Leary et al., 2011	36	21,2	50	Acute	Crossover	Inhibition	40
	Lambourne et al., 2010	19	21,1		Acute	Crossover	Cognitive Flexibility	40
	Sibley et al., 2007a	12	21,5	65	Acute	Crossover	Working Memory	30
	Sibley et al., 2007b	12	21,5	65	Acute	Crossover	Working Memory	30
	Sibley et al., 2007c	12	21,5	65	Acute	Crossover	Working Memory	30
	Sibley et al., 2007d	12	21,5	65	Acute	Crossover	Working Memory	30
	Stroth et al., 2009b	27	19,7	32	Chronic	RCT	Inhibition	900
	Sanabria et al., 2011	20	22	90	Acute	Crossover	Inhibition	20
	Joyce et al., 2009	10	23	70	Acute	Crossover	Inhibition	30

Note. RCT= Randomized Controlled Trial.

Table 2. Meta-analytic results

	Sample size	Number of studies	Meta-analytic effect size			Homogeneity		Publication bias		
			d	*95% CI*	*p*	*Q*	*p-value*	*p-value*	*Egger funnel plot*	*Fs N*
Acute physical exercise	586	19	.52	.29-.76	<.001	67.00	<.001	.15	304	.25
Preadolescent children	94	2	.57	.22-.92	<.05	2.02	<.001	n/a	n/a	n/a
Adolescents	169	3	.52	.26-.77	<.001	5.40		.33	9	.02
Young adults	323	14	.54	.22-.86	<.05	9.55		.48	54	.66
Executive function domains										
Inhibition/interference control	482	12	.46	.33-.60	<.001	17.90	.08	.25	140	.38
Preadolescent children	94	2	.57	.22-.92	<.05	2.02	.16	n/a	n/a	n/a
Adolescents	169	3	.52	.02-.78	<.001	5.40	.06	.33	9	.02
Young adults	172	7	.42	.24-.58	<.05	9.55	<.001	.48	54	.66
Working memory (only young adults)	48	4	.05	-.51-.61	.86	10.44	.15	.09	0	n/a
Chronic physical exercise	358	5	.14	-.04-.32	.19	5.1	.37	.65	0	.63
Executive function domains										
Planning (only preadolescent children)	337	3	.16	-.07-.39	.18	.89	.24	.73	0	.46

Note. Positive effect sizes indicate better performance of the experimental condition as compared to the control condition. n/a = not available; CI = confidence interval; Fs N = fail-safe N.

Study	Type	Mean age	Cohen's d	SE	95% CI		*p*-value
Preadolescent children							
Fischer et al., 2011	Chronic	6.10	0.00	0.25	-0.49	0.49	1.00
Kamijo et al., 2011	Chronic	9.00	0.0	0.17	-0.33	0.33	1.00
Ellemberg et al., 2010	Acute	9.10	0.81	0.25	0.33	1.29	0.00
Davis et al., 2011, high dose	Chronic	9.20	0.41	0.19	0.04	0.78	0.03
Davis et al., 2011, low dose	Chronic	9.20	0.00	0.19	-0.37	0.37	1.00
Hillman et al., 2009	Acute	9.60	0.31	0.26	-0.20	0.81	0.23
Combined effect size			0.23	0.13	-0.01	0.48	0.06
Adolescents							
Stroth et al., 2009a low fit	Chronic	14.20	0.18	0.25	-0.31	0.67	0.48
Stroth et al., 2009a high fit	Chronic	14.20	0.37	0.22	-0.06	0.81	0.09
Budde et al.,	Acute	14.90	0.89	0.21	0.48	1.31	0.00
Combined effect size			0.50	0.22	0.07	0.92	0.02
Young adults							
Stroth et al., 2009b	Chronic	19.70	0.69	0.39	-0.07	1.45	0.08
Audriffen et al., 2010	Acute	21.10	0.15	0.23	-0.31	0.60	0.52
Lambourne et al., 2010	Acute	21.10	0.74	0.32	0.12	1.36	0.02
O'Leary et al., 2011	Acute	21.20	0.42	0.17	0.08	0.76	0.02
Yanagisawa et al., 2010	Acute	21.50	1.05	0.28	0.50	1.60	0.00
Sibley et al., 2007 low	Acute	21.50	1.00	0.35	0.31	1.69	0.00
Sibley et al., 2007 middle-low	Acute	21.50	-0.21	0.29	-0.78	0.36	0.47
Sibley et al., 2007 middle-high	Acute	21.50	-0.41	0.30	-1.00	0.18	0.17
Sibley et al., 2007 high	Acute	21.50	-0.08	0.29	-0.64	0.49	0.80
Tomporowski et al., 2006	Acute	21.55	0.81	0.44	-0.06	1.68	0.07
Sanabria et al., 2011	Acute	22.00	0.65	0.32	0.02	1.29	0.04
Chang et al., 2011	Acute	22.11	2.76	0.43	1.91	3.60	0.00
Sibley et al., 2006	Acute	22.50	0.21	0.16	-0.09	0.52	0.17
Joyce et al., 2009	Acute	23.00	0.43	0.45	-0.45	1.32	0.34
Kamijo et al., 2007	Acute	25.70	0.77	0.41	-0.03	1.56	0.06
Combined effect size			0.55	0.16	0.24	0.85	0.00

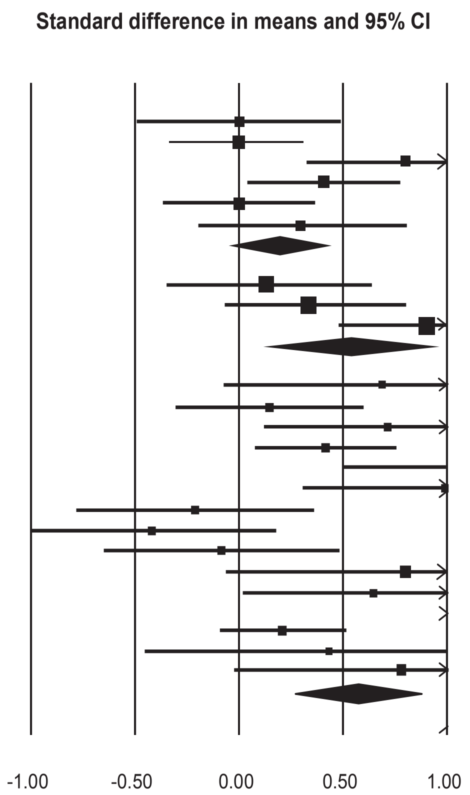

Figure 2. Effect sizes of individual studies. Positive effect sizes indicate better performance for the experimental condition as compared to control condition. SE = standard error; CI= confidence interval.

DISCUSSION

A moderate positive effect size of acute physical exercise on executive functions was found (*d*=0.52) in a sample of 586 participants derived from 19 studies. Inconsistent results were found on the effects of chronic physical exercise on executive functions, which resulted in a non-significant meta-analytic effect size (*d*=0.14) in a sample of 358 participants from five studies.

A majority of the studies examined the effects of acute physical exercise on inhibition/interference control, showing a small-to-moderate positive effect size across age groups (*d*=0.46) in a sample of 482 participants derived from 12 studies. These positive effects of physical exercise on inhibition/interference control are encouraging and highly relevant, given the importance of inhibitory control and interference control in daily life. Inhibition is essential for regulation of behavior and emotions in social, academic and sport settings (Scheres, Oosterlaan, Geurts, Morein-Zamir, Meiran, Schut, et al., 2004; Mostofsky & Simmonds, 2008). The importance of inhibitory control and interference control is illustrated by children with attention deficit/hyperactivity disorder (ADHD), who show impaired inhibition performance as a key cognitive deficit. In ADHD, impaired inhibition is thought to lead to a cascade of adverse developmental outcomes including cognitive performance, disruptive behavior, impaired social skills and poor academic performance (Scheres et al., 2004). Interestingly, some positive effects of physical training have been reported in children with ADHD on both behavioral symptoms and cognitive deficits (Tantillo, Kesick, Hynd et al., 2002; Maddigan & Hodgeson, 2003).

Although many studies have argued that physical exercise may have stronger effects on executive functions than on other cognitive functions, (Colcombe et al., 2003; Alvarez & Emory, 2006), the literature lacks an explanation for such selective effects of physical exercise on executive functions. It may be speculated that a stronger elevation of CBF and cerebral oxygenation, possibly mediated by better vascularization, in (pre)frontal brain areas as compared to other brain areas, accounts for selective effects of acute physical exercise on executive functions (Hiura, Mizuno, & Fujimoto, 2010; Seifert & Secher, 2011). The possible positive effects of chronic physical exercise on executive functions may be explained by the improved structural connectivity of the prefrontal brain areas. It has been shown that white matter integrity in the prefrontal cortex is important for executive functioning. The performance of children on an inhibition task was found to be positively related to white matter integrity in the presupplementary motor cortex and inferior frontal cortex (Madsen, Baaré, Vestergaard et al., 2010), while reduced white matter integrity in normal ageing participants was associated with poor inhibitory control (Oosterman, Vogels, Van Harten et al., 2008). Interestingly, Marks and colleagues (2007) showed that higher levels of aerobic fitness are associated with greater white matter integrity in prefrontal brain areas. Consequently, it may be suggested that higher aerobic fitness levels may help in maintaining or promoting the structural connectivity of the frontal brain areas, mediating the positive effects of physical exercise on executive functions, as was also suggested by Colcombe and colleagues (2006).

Physical exercise may be especially relevant for children, adolescents and young adults at risk of obesity. A recent meta-analysis showed that children and adolescents with obesity had cognitive deficits that were most prominent for executive functions (Smith, Hay, Campell et al., 2011). This may be explained by decreased levels of CBF in predominantly prefrontal brain areas (Selim, Jones, Novak et al., 2008; Willeumier, Taylor, & Amem, 2011). Therefore, physical exercise may provide a promising intervention for executive function deficits of children with obesity, possibly by prolonged enhancement of CBF in the frontal brain regions. Furthermore, it has been shown that body mass index (BMI) is negatively associated with cognitive functioning (Li, Dai, Jackson et al., 2008; Shore, Sachs, Lidicker et al, 2008). In other words, it might be suggested that for overweight children, regular physical exercise has a beneficial effect on executive functions, mediated by a decrease in BMI. Interestingly, the only study reporting a significant positive effect of chronic exercise on executive functions was a study of overweight children, which investigated the effects of 40 min sessions of physical exercise (Davis et al., 2011).

Besides the relevance for overweight children, adolescents and young adults, the present results also have repercussions for treatment of disorders associated with executive function deficits, including, for example, ADHD, obsessive-compulsive disorder and autism (Zelazo & Müller, 2010). Physical exercise may be an effective method for improvement of executive functioning in these populations. Furthermore, evidence showed that people with a physically active lifestyle have a higher ‘cognitive reserve’, which may delay the progressive decline of cognitive functioning in healthy ageing and clinical populations, including people with dementia (Stern, 2002). Given the trend for a more sedentary lifestyle, worldwide ageing and the increasing prevalence of dementia (Lautenschlager, Almeida, Flicker et al., 2004), the results highlight the importance of engaging in physical exercise in the general population.

This meta-analysis has some limitations. First, a majority of the studies assessed the effects of acute physical exercise on inhibition/interference control in young adults. Consequently, the meta-analytic effect sizes for other executive function domains were based on a smaller number of studies. The findings on working memory should especially be interpreted with caution, as the meta-analytic results are based on only four studies. Nevertheless, current results are consistent with the findings on working memory in the meta-analysis of Smith et al (2011) who found incoherent results on the effects of physical exercise on the working memory in the elderly. Also, only five studies addressed the effects of chronic physical exercise on executive functions, of which three assessed planning. Therefore, no conclusions can be drawn on the effects of chronic physical exercise on different executive function domains. Moreover, almost all studies investigating the effects of acute physical exercise were crossover designs, whereas the studies on the chronic effects of physical exercise were all RCTs. Although both types are high-quality experimental designs, the analyses in the individual studies may differ as a result of the design, causing the meta-analytic results to be significantly confounded.

Second, only 12 of the 25 studies monitored the heart rate of the participants, making it impossible to investigate the role of exercise intensity on the effects of exercise on executive functions. This is an important issue because a growing body of evidence suggests that moderate physical exercise appears to be more favorable for cognitive functions as compared to light and vigorous physical exercise. Moderate physical exercise is defined in terms of maximal oxygen uptake (VO2max) and maximal heart rate (HRmax), and it is suggested that the optimal intensity should be around 60% of VO2max and HRmax (Davranche & McMorris, 2009; Kashihara et al., 2009). Another interesting observation is that the inconsistent results of the studies reporting on the effects of chronic physical exercise may be interpreted as suggesting that chronic physical exercise possibly leads to a smaller positive effect on executive functioning as compared to the effects of acute physical exercise. This may be related to the delayed nature of the neurophysiological processes in response to chronic physical exercise (eg, angiogenesis and neurogenesis) as compared to the acute neurophysiological responses (ie, increased CBF). In other words, it might be that the interventions in the present meta-analysis on the effects of chronic physical exercise on executive functions were not suitable in terms of the intensity, frequency and duration of the exercise intervention to enhance executive functioning. The discrepant findings for chronic and acute physical exercise may also be related to differences in the timing of the executive function assessment. In most studies on acute physical exercise, assessment took place immediately after the intervention, whereas most studies on chronic physical exercise did not provide details on the timing of the assessment, suggesting that assessments were not scheduled immediately after the exercise intervention.

We recommend that, in future research, it should be investigated whether chronic physical exercise shows effects on executive functions comparable to acute physical exercise. This is of great relevance because regular physical exercise may not only improve executive functions but also have other beneficial effects including decrease of the risk for cardiovascular diseases (Warburton et al., 2006). Furthermore, although the current meta-analysis suggests that there are no age-related differences in the effects of physical exercise on executive functioning, more research on preadolescent children and adolescents is needed to draw firm conclusions on whether the effects of regular physical exercise are similar for preadolescent children, adolescents and young adults. This is relevant in respect of children with diseases and disorders, including obesity, diabetes, ADHD and autism, who show deficits in executive functions and may benefit more from physical exercise interventions at younger ages, when cognitive functioning is strongly proliferating. Additionally, it is recommended that future studies monitor the heart rate to improve comparability between studies. Connected to this, there is a need for high-quality RCTs manipulating intensity (ie, light, moderate and vigorous) and duration (eg, 10, 30 and 60 min) of physical exercise interventions to enhance the understanding of the optimal balance between the intensity and duration of physical exercise and the effects on executive functions.

In conclusion, the present meta-analysis has important implications. First, the results suggest that acute physical exercise enhances executive functioning, which is highly relevant in preadolescent children and adolescents, given the importance of well-developed executive functions for academic achievement and daily life functioning (Anderson, Anderson, Northam et al., 2002; Brock, Rimm-Kaufman, Nathanson et al., 2009; Willoughbym, Kupersmidt & Voegler-Lee, 2012). Second, the results of the present meta-analysis might pave the road for interventions using physical exercise to enhance executive functions in individuals with disorders characterized by executive function deficits. Also, the results are highly relevant, given the current increase in obesity in children and adolescents and the increase in sedentary behavior in these age-groups (Ogden, Carroll, Curtin et al., 2006).

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