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Effects of physical activity interventions on cognitive outcomes and academic performance in adolescents and young adults: A meta-analysis

Barbara Franca Haverkamp^a, Rikstje Wiersma^b, Karen Vertessen^c, Hanneke van Ewijk^d, Jaap Oosterlaan^e and Esther Hartman^f

^aUniversity of Groningen, University Medical Center Groningen, Center for Human Movement Sciences, Groningen, The Netherlands and Vrije Universiteit Amsterdam, Faculty of Behavioural and Movement Sciences, Clinical Neuropsychology Section, Amsterdam, The Netherlands;

^bDepartment of Epidemiology, University of Groningen, University Medical Center Groningen, Groningen, The Netherlands; ^cFaculty of Behavioural and Movement Sciences, Clinical Neuropsychology Section, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands; ^dCurium-LUMC, Department of Child and Adolescent Psychiatry, Leiden University Medical Center, Oegstgeest, The Netherlands; ^eVrije Universiteit Amsterdam, Faculty of Behavioural and Movement Sciences, Clinical Neuropsychology Section, Amsterdam, the Netherlands and Emma Children's Hospital, Amsterdam UMC, University of Amsterdam and Vrije Universiteit Amsterdam, Emma Neuroscience Group, Department of Pediatrics, Amsterdam Reproduction & Development, Amsterdam, the Netherlands; ^fUniversity of Groningen, University Medical Center Groningen, Center for Human Movement Sciences, Groningen, The Netherlands

ABSTRACT

The aim was to provide a meta-analysis of studies investigating the effects of physical activity interventions on cognitive outcomes and academic performance in adolescents or young adults. A systematic review with meta-analysis was performed using the following databases: Embase, ERIC, MEDLINE, PsycINFO and Web of Science. Studies had to meet the following criteria: controlled study design, investigating the effects of physical activity interventions on cognitive outcomes and academic performance in healthy adolescents or young adults (12–30 years). Results showed that acute interventions ($n=44$) significantly improved processing speed ($ES=0.39$), attention ($ES=0.34$) and inhibition ($ES=0.32$). In a subsequent meta-regression, shorter duration of intervention was significantly associated with greater improvements in attention ($\beta=-0.02$) and cognitive flexibility ($\beta=-0.04$), whereas age, percentage of boys, intensity and dose were not. Chronic interventions ($n=27$) significantly improved processing speed ($ES=0.30$), attention ($ES=0.50$), cognitive flexibility ($ES=0.19$), working memory ($ES=0.59$) and language skills ($ES=0.31$). In the meta-regression, higher percentage of boys was significantly associated with greater improvements in attention ($\beta=0.02$) and working memory ($\beta=0.01$) whereas age, duration, frequency, dose and load were not. In conclusion, acute and chronic physical activity interventions might be a promising way to improve several cognitive outcomes and language skills in adolescents and young adults.

ARTICLE HISTORY

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KEYWORDS

Cognition; academic achievement; acute exercise intervention; chronic exercise intervention

Introduction

Physical activity confers strong positive health benefits, including lower risks of cardiovascular diseases (Janssen & LeBlanc, 2010; Li & Siegrist, 2012), adiposity (Haynos & O'Donohue, 2012) and type 2 diabetes (Stanford & Goodyear, 2014). Recent research has also linked physical activity to cognitive and academic benefits in both children and older adults (Esteban-Cornejo et al., 2015; Hillman et al., 2008; Northey et al., 2017). Despite the benefits of physical activity, nowadays more than 80% of adolescents do not adhere to the recommended physical activity guidelines (Piercy et al., 2018). The lack of physical activity is seen as a major threat for physical and cognitive health.

Physical activity is especially important during adolescence and young adulthood. During this stage of development, higher cortical functions, the so-called executive functions, which are located in the prefrontal cortex show rapid development (Lebel et al., 2008; Lenroot & Giedd, 2006). A growing number of studies have supported the idea that physical activity boosts these executive functions (Li et al., 2017; Verburch et

al., 2013; Xue et al., 2019). Furthermore, physical activity might also have a positive effect on attention and processing speed. These are two basic neurocognitive functions that act as prerequisite for executive functions to emerge. Furthermore, neurocognitive functions are an important prerequisite for successful learning (Brown & Blanton, 2002; Diamond, 2013), and executive functions are indispensable for success throughout life (Diamond & Lee, 2011). In terms of brain development, grey and white matter have been found to continue developing up to 30 years of age, with the most prominent changes taking place in the prefrontal cortex (Lebel et al., 2008; Lenroot & Giedd, 2006; Tamnes et al., 2017; Whitford et al., 2007). Therefore, cognitive outcomes and academic performance might not be ideally optimized and supported since these functions strongly rely on frontal lobe functioning.

There are some physiological mechanisms supposed to underlie the supposed beneficial effects of physical activity on cognitive outcomes and academic performance. A single bout of physical activity (also referred to as acute physical activity) increases cerebral blood flow and neurotransmitter secretion

levels, resulting in increased levels of arousal, attention and effort, which in turn positively influence the performance on cognitive tasks shortly after performing physical activity (Best, 2010; Kashiwara et al., 2009; Tomporowski, 2003). Repeated bouts of physical activity (also referred to as chronic physical activity or chronic exercise) has been shown to lead to angiogenesis (Best, 2010), synaptogenesis and neurogenesis (Hillman et al., 2015; Ross et al., 2015). Such morphological changes in brain structure may lead to enhanced cognitive outcomes and academic performance (Best, 2010). Due to the resulting structural changes, effects of a chronic intervention may persist longer.

The existing literature mostly focuses on acute physical activity interventions in preadolescent children (Fedewa & Ahn, 2011; De Greeff et al., 2018; Lees & Hopkins, 2013) or elderly populations (Angevaren et al., 2007; Northey et al., 2017). Relatively little is known about the age group of adolescents and young adults, and about the effects of chronic physical activity (Li et al., 2017; Verburgh et al., 2013; Xue et al., 2019). Furthermore, most studies focus on cognitive outcomes, while few studies describe effects of physical activity interventions on academic performance (Haapala, 2012). However, in the last decade new research is emerging in these topics. Therefore, it is important to get a full overview of the effects of acute- and chronic physical activity interventions on cognitive outcomes and academic performance in adolescents and young adults.

The aim of this paper is to provide a meta-analysis of studies investigating the effects of physical activity interventions on cognitive outcomes and academic performance in adolescents or young adults. We distinguished between studies addressing effects of acute and chronic physical activity. If possible, we distinguished between subdomains of cognitive outcomes and subdomains of academic performance. Moderator analyses were conducted to provide insight into the possible moderating effects of the nature of the sample studied, study and intervention characteristics and study quality.

Method

The protocol of this meta-analysis was registered in the International Prospective Register of Systematic Reviews (PROSPERO; CRD42019122030). This review was conducted in accordance with the guidelines from Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Moher et al., 2009).

Inclusion and exclusion criteria

This meta-analysis included all studies examining the effects of physical activity interventions on cognitive outcomes and academic performance published in peer-reviewed English language journals. The search included all studies indexed till the 27th of March 2020. The selection of studies was based on multiple inclusion criteria. First, the physical activity intervention had to contain a sports or exercise component. Both acute physical activity interventions (one bout of physical activity) and chronic physical activity interventions (an intervention programme that contains continuous physical activity over

several days) were selected. Second, the mean age of the participants in the sample had to be between 12 and 30 years (Rindfuss, 1991). This age range includes adolescents from later-puberty till early adulthood (American College of Sports Medicine, 2013). If no mean age was given then the age range of the sample had to be between 10 and 32 years old. Third, the studies had to use a controlled design, with or without random allocation. If no random allocation was used, adequate adjustment for baseline differences between groups was required (e.g., analyses of covariance). Fourth, the study had to report on outcomes that were of interest in the present article (e.g., processing speed, attention, executive function or academic performance) before and after the intervention. The following studies were excluded from the current meta-analysis: 1. studies targeting special populations, as generalisation of findings of these studies would be limited (e.g., adolescents or young adults with mental or cognitive disorders, nervous system diseases or brain injuries), 2. reviews, and 3. studies that combined a physical activity intervention with another intervention such as nutrition.

Search strategy

The electronic databases Embase, ERIC, MEDLINE, PsycINFO and Web of Science were searched for relevant studies. The search string combined four elements including terms describing 1. the physical activity intervention, 2. the age group studied, 3. the neurocognitive or academic outcome studied and 4. the study design used. The complete search string is provided in Appendix A.

After removal of duplicates, the first author BH and a trained research assistant independently screened the titles and abstracts to assess eligibility criteria. Following this, full-text articles were assessed independently by the first author BH and another trained research assistant. Disagreements were discussed and consensus was reached together. If multiple articles included the same participants and reported on the same outcome measure, the article with the largest sample size was selected. Reference lists of included studies were further examined as complementary sources.

Data extraction

Sample descriptives, study design, outcome measures and characteristics of the intervention were independently extracted by two review authors (BH, RW). Mean and accompanying standard deviations (SDs) were extracted for all outcome measures. If a study collected data at multiple time points, only baseline scores and scores closest to the end of the intervention were used. If a study reported the outcome of interest in multiple subgroups (e.g., fit vs. unfit or high vs. low social economic status), the mean of the subgroups weighted by their sample sizes was used in the analyses (Moher et al., 2009). If p values were reported as $p < 0.05$, we assumed a p value of 0.05 in order to calculate the standard error and the accompanying 95% CI. If p values were reported as $p > 0.05$, we assumed a p -value of 0.53 (i.e. the average of 0.05 and 1.00) in order to calculate the standard error and 95% CI (Bland, 2013). If multiple intervention groups were compared to the same

control group, the sample size of the control group was divided by the number of intervention groups. If data required to calculate effect sizes were missing, authors were contacted to request the missing information. The effects sizes (ESs) were corrected for study design by the Comprehensive Meta-Analysis software (version 3). Given that all outcome measures were recorded as continuous measures, the standardized mean difference (SMD) was used to quantify the effect size.

Risk of bias assessment

Two authors (BH, RW) independently assessed the risk of bias of the included studies following the Cochrane Collaboration tool for assessing Risk of Bias (Higgins et al., 2011). This tool addressed six domains: selection bias, performance bias, detection bias, attribution bias, reporting bias and other bias. For each of these domains risk of bias was judged distinguishing between low risk of bias, high risk of bias or unclear risk of bias. Discrepancies regarding risk of bias were discussed until consensus was reached.

Statistical analysis

Statistical analysis was performed using Comprehensive Meta-Analysis. First, separate meta-analyses were conducted for acute and chronic physical activity interventions, thereby distinguishing between cognitive outcomes and academic performance. Second, based on the literature, a subgroup analysis was conducted for several subdomains. Subdomains of cognitive outcomes included: processing speed, attention and executive function. Executive functions were further separated into cognitive flexibility, working memory, and inhibition. The subdomains of academic performance were grade point average, language and mathematics. Third, to control for dependency between multiple outcome variables (e.g., accuracy and reaction time) within a subdomain (e.g., processing speed), a mean effect size was calculated across the related outcome measures. Finally, heterogeneity was assessed using the X^2 test and the I^2 statistic. If study results were heterogeneous ($I^2 > 50\%$ or X^2 test p value < 0.05), the calculated effect size cannot be treated as estimate of a common effect size. In that case, a moderator analysis was conducted to study possible sources of the heterogeneity. Moderator analyses tested the effects of study, sample and/or intervention characteristics. If possible, moderator analyses were performed for type of intervention, type of control condition, study design and way of testing in academic performance. For each meta-analyses, moderator analyses were only performed if each category of the potential moderator was filled with at least three studies (Borenstein et al., 2011). If there were ten or more than ten studies, and the moderator was a continuous variable, a meta-regression was performed (Borenstein et al., 2011). This was the case in acute interventions for age, percentage of boys, duration (min), intensity and dose (duration $\times$ intensity). For chronic interventions, meta-regression analyses were performed for: age, percentage of boys, duration (weeks), frequency (times per week), dose (min per week), load (min per intervention) and difference in physical fitness levels. The effect sizes were

corrected for small sample bias (Hedges' g) and reported with 95% confidence intervals (CIs). The magnitude of Hedges' g was interpreted using Cohen's guidelines, distinguishing between small (< 0.2), moderate (0.5), and large (> 0.8) effect sizes (Cohen, 1988). Positive effect sizes favoured the exercise group while negative effect sizes favoured the rest/control group. A random effects approach was used to compute effect sizes. The presence of publication bias was assessed by using a funnel plot and performing the Egger's linear regression method. Statistical significance was adopted for all tests when $p < 0.05$.

Results

The initial search in the databases netted 15,222 records. After removing duplications and screening the titles, 427 papers were eligible for further screening (see Figure 1). One hundred and seventy papers were read full text and a further 99 papers not meeting the inclusion criteria were excluded. In total 71 papers were eligible for this review and meta-analysis. Overall, 44 studies (Aguirre-Loaiza et al., 2019; Akatsuka et al., 2015; Basso et al., 2015; Benzing et al., 2016; Browne et al., 2016; Budde et al., 2010, 2008; Chang & Etnier, 2009; Chang et al., 2011; Coles & Tomporowski, 2008; Cooper et al., 2016, 2012; ÉW et al., 2011; Guzmán & López-García, 2016; Hwang et al., 2016; Hwang & Lu, 2018; Jaffery et al., 2018; Lambourne, 2012; Lambourne et al., 2010; Ludyga, Pühse, et al., 2019; Mezcuca-Hidalgo et al., 2019; Moore et al., 2012; Murray & Russoniello, 2012; Palmiere et al., 2018; Peruyero et al., 2017; Pontifex et al., 2009; Prashanth, 2020; Du Rietz et al., 2019; Schwarck et al., 2019; Sipavičienė et al., 2012; Sperlich et al., 2018; Takahashi et al., 2019; Tine, 2014; Tine & Butler, 2012; Tsai et al., 2014, 2016; Tsorbatzoudis et al., 1998; Tsukamoto et al., 2017; Van den Berg et al., 2018; Vonk et al., 2019; Wang et al., 2015; Whyte et al., 2014; Zhou & Qin, 2019; Zimmer et al., 2016) investigated the effects of acute physical activity interventions, and 27 studies (Arday et al., 2014; Butzer et al., 2015; Costigan et al., 2016; Duarte et al., 2020; Hagins & Rundle, 2016; Heisz et al., 2017; Jeon & Ha, 2017; Johann et al., 2016; Kauts & Sharma, 2009; Lennemann et al., 2013; Ludyga, Gerber, Herrmann, et al., 2018; Ludyga, Gerber, Kamijo, et al., 2018; Ludyga, Köchli, et al., 2019; Matthews et al., 2016; Pinto-Escalona & Martínez-de-Quel, 2019; Purohit & Pradhan, 2017; Sharma et al., 2015; Sjöwall et al., 2019; Spitzer & Hollmann, 2013; Stroth et al., 2009, 2010; Subramanian et al., 2015; Tarp et al., 2016; Torbeyns et al., 2017; Venckunas et al., 2016; Woost et al., 2018; Zheng et al., 2015) investigated the effects of chronic physical activity interventions.

Study characteristics

Taken together, the studies included 3544 adolescents and 2397 young adults. Academic performance was only assessed in adolescents and not in young adults. Appendix B1 and B2 show the extracted details from the studies incorporated in this meta-analysis, including: mean age, sample size, outcome (measurement), in- and exclusion criteria and characteristics of the tested intervention: type, dose, frequency, duration and intensity.

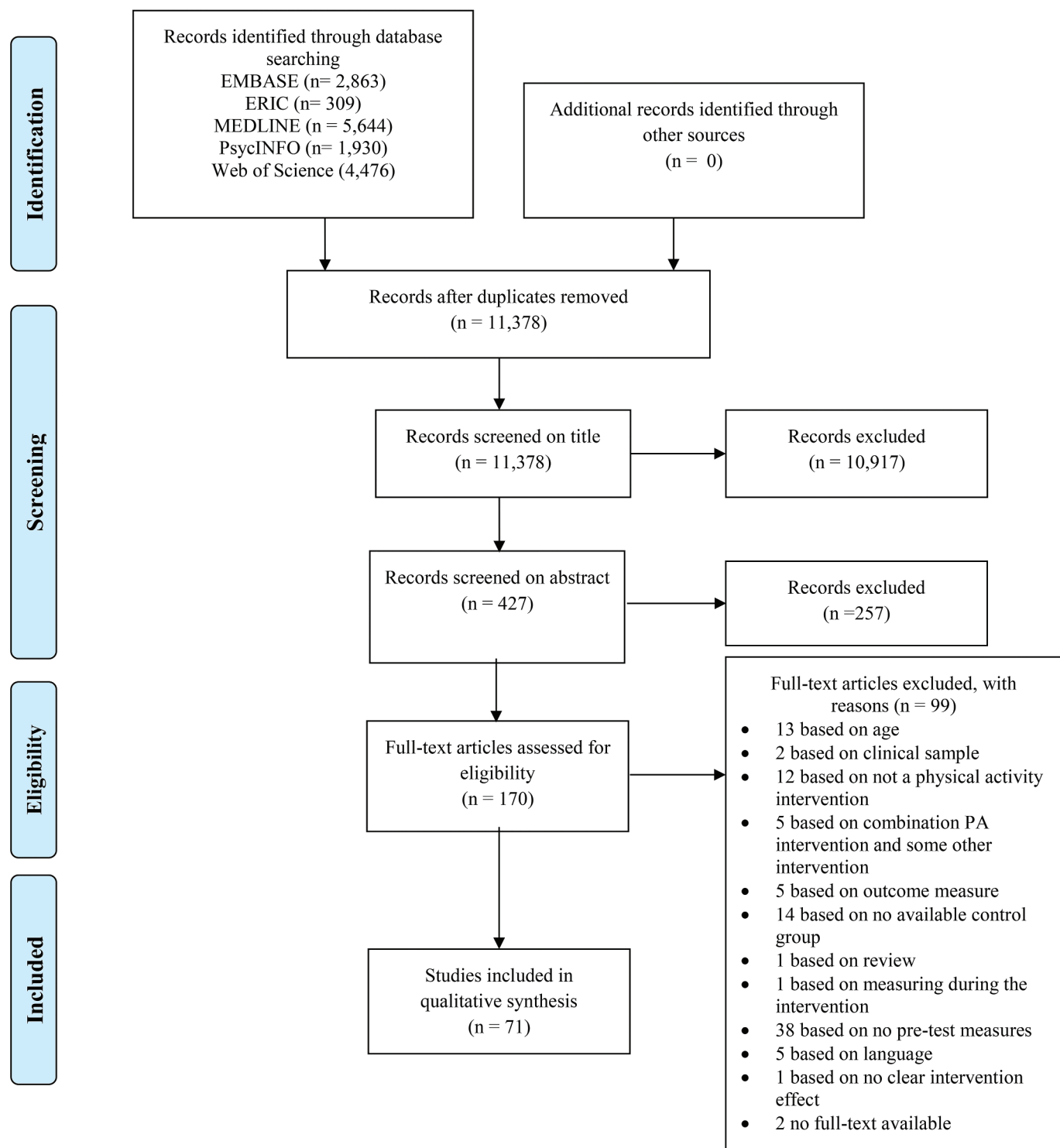


Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) flow diagram of each stage of the study selection.

Effects of physical activity interventions

The calculated effect sizes and heterogeneity statistics are shown in Table 1 and Figures 2(a,b). Meta-analytic effects were calculated separately for the acute and chronic intervention studies. Furthermore, meta-analytic effects were calculated for different subdomains of cognitive outcomes and academic performance. As heterogeneity was present in executive

functions, this subdomain was further subdivided into cognitive flexibility, working memory and inhibition.

Effects of acute physical activity interventions

Forty-four studies ($k = 91$) examined the effects of acute physical activity interventions on cognitive outcomes or

Table 1. Meta-analytic results of the effects for physical activity interventions on cognitive outcomes and academic performance.

Table 1. Meta-analytic results of the effects for physical activity interventions on cognitive outcomes and academic performance.								
Outcome	Sample size	<i>k</i>	Meta-analytic effect size			Heterogeneity		
			Hedges' <i>g</i>	95%CI	<i>p</i> value	<i>I</i> ²	<i>Q</i>	<i>p</i> value
Acute intervention								
Cognitive outcomes	4938	91	0.312	[0.219,0.406]	<0.001	64.9	256.5	<0.001
Processing speed	694	8	0.394	[0.072,0.716]	0.017	70.4	23.6	0.001
Attention	1123	18	0.340	[0.134,0.545]	0.001	66.6	50.9	<0.001
Executive functions	2893	63	0.294	[0.191,0.398]	<0.001	63.0	167.4	<0.001
Cognitive flexibility	692	15	0.372	[−0.000,0.745]	0.050	82.7	81.1	<0.001
Working memory	680	12	0.140	[−0.106,0.386]	0.264	58.1	26.3	0.006
Inhibition	1479	35	0.319	[0.196,0.442]	<0.001	38.0	54.8	0.013
Chronic interventions								
Cognitive outcomes	4715	52	0.364	[0.254,0.473]	<0.001	62.1	134.9	<0.001
Processing speed	694	2	0.297	[0.148,0.446]	<0.001	0	0.3	0.611
Attention	1063	11	0.499	[0.260,0.738]	<0.001	68.6	31.9	<0.001
Executive functions	2671	34	0.354	[0.207,0.501]	<0.001	60.2	82.9	<0.001
Cognitive flexibility	869	11	0.189	[0.049,0.329]	0.008	0.0	7.8	0.646
Working memory	699	14	0.587	[0.274,0.900]	<0.001	68.9	41.8	<0.001
Inhibition	1103	9	0.155	[−0.050,0.361]	0.139	46.4	14.9	0.061
Academic performance	2127	15	0.338	[0.187,0.489]	<0.001	62.6	37.7	0.001
GPA	262	4	0.201	[−0.044,0.446]	0.108	0	2.6	0.461
Language	347	5	0.310	[0.129,0.492]	0.001	0	2.2	0.818
Mathematics	1142	7	0.310	[−0.014,0.633]	0.061	77.9	27.2	<0.001

k, number of effect sizes; GPA, Grade Point Average.

academic performance. Only one study focused on academic performance, while the other 43 studies focused on cognitive outcomes. No meta-analysis was conducted for academic performance. Overall, acute physical activity resulted in a moderate effect on cognitive outcomes (Hedges's *g* = 0.31; 95% CI 0.22 to 0.41). Heterogeneity in effect sizes was large (I^2 = 64.9%, p < 0.001). Further analyses distinguishing between core domains of cognitive outcomes, showed a significant moderately sized effect for processing speed (Hedges's *g* = 0.39; 95% CI 0.07 to 0.72), a significant moderately sized effect for attention (Hedges's *g* = 0.34; 95% CI 0.13 to 0.55) and, a significant moderately sized effect for executive functions (Hedges's *g* = 0.29; 95% CI 0.19 to 0.40). Heterogeneity was large for all three effects (see Table 1). A further distinction between executive functions yielded a significant moderately sized effect for inhibition (Hedges's *g* = 0.32; 95% CI 0.20 to 0.44), but no effects for cognitive flexibility (Hedges's *g* = 0.37; 95% CI −0.00 to 0.75), and working memory (Hedges's *g* = 0.14; 95% CI −0.11 to 0.39).

Moderator analysis

Moderator analyses were performed for attention, cognitive flexibility, working memory and inhibition because heterogeneity was present in these domains. Table 2 summarises the results of these analyses.

Analyses with categorical moderators showed that the effects of acute physical activity interventions was not significantly different between RCT and cross-over studies in working memory and inhibition. Furthermore, there was no significant difference between studies contrasting the effects of acute physical activity to a rest condition or a condition involving some physical activity as a control condition. Other moderator analyses could not be performed due to the small number of studies available in the subgroups.

In the meta-regressions, longer duration of the intervention was inversely related to the effects on attention (β = −0.021, 95% CI −0.04 to −0.01, p = 0.006) and cognitive flexibility (β = −0.036, 95% CI −0.06 to −0.01, p = 0.012). Duration of the

intervention was not significantly related to the effects for working memory and inhibition. Furthermore, higher dose of the intervention was inversely related to the effects of attention (β = −0.00; 95% CI −0.00 to 0.00, p = 0.028). Dose of the intervention was not significantly related to effects for working memory and inhibition. Age, percentage of boys and intensity were not significantly related with the studies' effect sizes for any of the cognitive domains or there were too few to perform the meta regression analyses.

Effects of chronic physical activity interventions

Twenty-seven studies examined the effects of chronic physical activity interventions on cognitive outcomes (k = 52) or academic performance (k = 15). Overall, chronic physical activity interventions had a moderate effect on cognitive outcomes (Hedges's *g* = 0.36; 95% CI 0.25 to 0.47). There was moderate heterogeneity in the individual studies' effect sizes (I^2 = 62%, p < 0.001). Further analyses distinguishing between core domains of cognitive outcomes showed three significant moderately sized effects for: processing speed (Hedges's *g* = 0.30; 95% CI 0.15 to 0.45), attention (Hedges's *g* = 0.50; 95% CI 0.26 to 0.74), and executive functions (Hedges's *g* = 0.35; 95% CI 0.21 to 0.50). Heterogeneity was large for all three effects (see Table 1). A further distinction between executive functions yielded a significant small sized effect for cognitive flexibility (Hedges's *g* = 0.19; 95% CI 0.05 to 0.33) and a significant large sized effect for working memory (Hedges's *g* = 0.59; 95% CI 0.27 to 0.90), but no effect for inhibition (Hedges's *g* = 0.16; 95% CI −0.05 to 0.36).

Furthermore, chronic physical activity interventions had a significant moderately sized effect on academic performance (Hedges's *g* = 0.34; 95% CI 0.19 to 0.49). Heterogeneity in effect sizes was moderate (I^2 = 63%, p = 0.001). Further analyses distinguishing between core domains of academic performance showed a significant moderately sized effect for

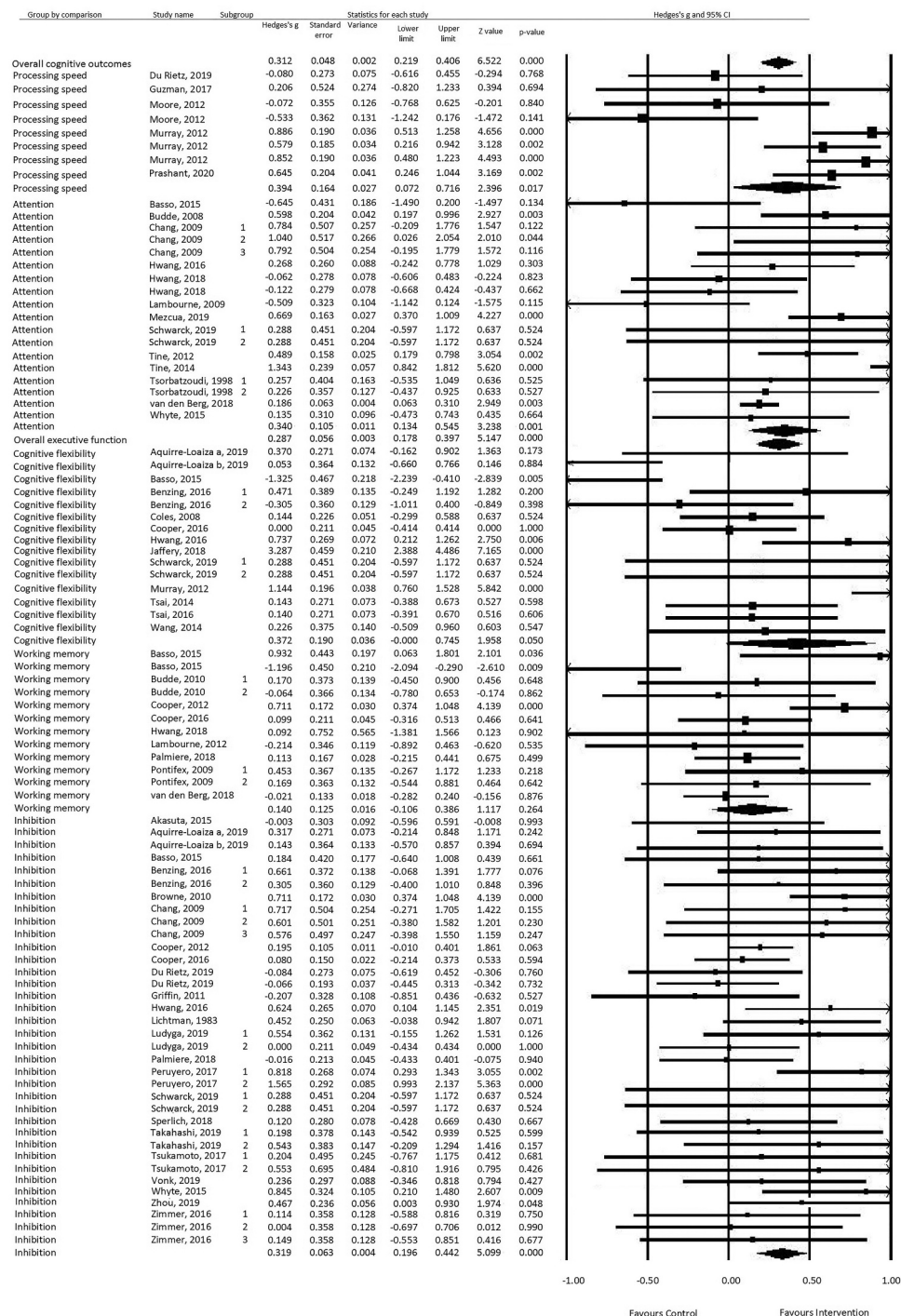


Figure 2. (a) Forest plot for meta-analysis regarding the effect of acute physical activity interventions on different cognitive outcomes. (b) Forest plot for meta-analysis regarding the effect of chronic physical activity interventions on different cognitive outcomes and academic performance.

language (Hedges's $g = 0.31$; 95% CI 0.13 to 0.49), but no effects for grade point average (Hedges's $g = 0.20$; 95% CI -0.04 to 0.45) and mathematics (Hedges's $g = 0.31$; 95% CI -0.01 to 0.63).

Moderator analysis

Moderator analyses were performed for attention, working memory, and mathematics, since heterogeneity was present

in these domains. Table 2 summarises the results of the subgroup analysis and the meta-regressions. None of the domains had a sufficient number of studies to perform a subgroup analysis (design, type of intervention, control condition or way of testing in academic performance).

In the meta-regressions, percentage of boys was significantly and inversely related to the effects of attention ($\beta = 0.02$; 95% CI 0.00 to 0.03, $p = 0.021$) and working memory ($\beta = 0.01$; 95% CI 0.00 to 0.03, <

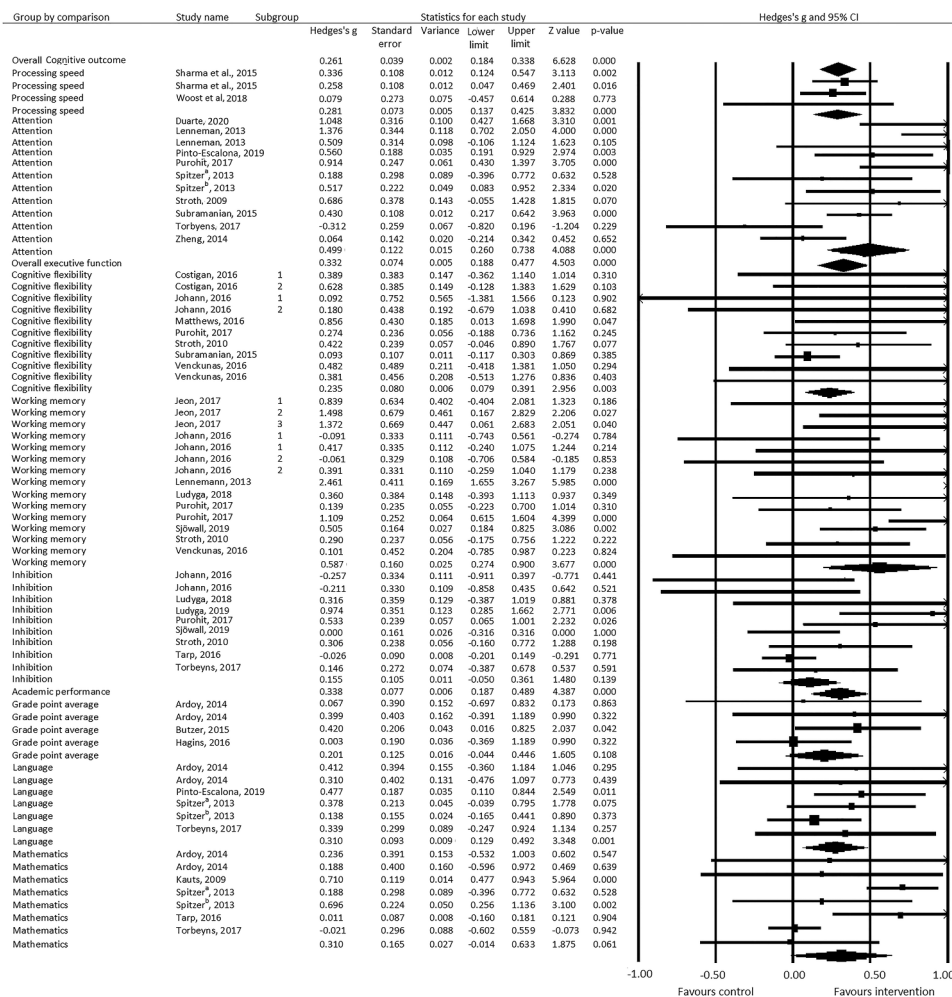


Figure 2. (Continued).

frequency were not significantly related with the studies' effect sizes in attention. There were not enough studies reporting dose, load and difference physical fitness to calculate their relation to the effect on attention. For working memory, age, duration, frequency, dose and load were not significantly related with the studies' effect sizes. There were not enough studies reporting difference in physical fitness to calculate the relation to working memory's effect size. Finally, meta-regression analysis could not be performed for mathematics due to the small number of studies available.

Risk of bias

Risk of bias was assessed using the Cochrane risk of bias tool and the results are summarized in Figure 3. First, selection bias was assessed by sequence generation and allocation concealment. Most of the included studies (63.0%) did not provide a sufficient description of the process of sequence generation which made it impossible to assess the risk of bias. Therefore, these studies were judged as having an unclear risk of bias for sequence generation. In addition, the majority of the studies (65.8%) did not describe the allocation concealment and were consequently judged as having high risk of bias. Second, performance bias was assessed by blinding the researchers and blinding those who

delivered the intervention. In most studies it was not possible to blind researchers and those involved in delivering the intervention (91.8% and 97.3% respectively), therefore most studies were scored as having a high risk of bias. Third, detection bias was assessed by blinding the researchers during the measurements. In most studies this was not reported and scored as high risk of bias (84.9%). Fourth, the attrition bias was assessed by risk of bias due to incomplete data and was scored as low risk in most studies (82.2%). Fifth, reporting bias was assessed by the risk of bias due to selective reporting and this was judged as not available in most studies (87.7%). Sixth, no other sources that could have caused bias were observed.

Publication bias

The funnel plot and the Egger's regression procedure indicated that there was neither evidence for publication bias for any of the outcome measures in the acute intervention studies ($p = 0.653$) nor for any of the academic performance in the chronic intervention studies ($p = 0.926$). However, the funnel plot and the Egger's regression procedure indicated that there were indications for the presence of publication bias for the cognitive outcome measures in the chronic physical activity intervention studies ($p = 0.007$), see Appendix C. Therefore,

Table 2. Results of moderator analyses and meta-regression analyses.

ACUTE INTERVENTIONS								
Attention								
Continuous moderator	Level	No. of studies	β	95% CI	I2%	Q	df	p-value
Age, years	12.3 to 26	18	-0.026	[-0.074,0.023]	68.3	1.1	1	0.300
Boys, %	40.0 to 100	18	-0.008	[-0.011,0.009]	68.4	0.0	1	0.869
Duration, min	5 to 60	18	-0.021	[-0.035,-0.006]	56.3	7.4	1	0.006
Intensity, bpm	94.9 to 188	13	-0.004	[-0.013,0.006]	61.6	0.5	1	0.473
Dose (min $\times$ bpm)	889 to 9678	13	-0.000	[-0.000,0.000]	50.5	4.9	1	0.028
Cognitive flexibility								
Continuous moderator	Level	No. of studies	β	95% CI	I2%	Q	df	p-value
Age, years	12.6 to 23.6	15	0.030	[-0.079,0.140]	83.3	0.3	1	0.589
Boys, %	20.5 to 100	13	-0.011	[-0.025,0.004]	84.5	2.2	1	0.141
Duration, min	5 to 60	15	-0.036	[-0.064,-0.008]	82.3	6.3	1	0.012
Working memory								
Categorical moderator	Level	No. of studies	Cohen <i>s d</i>	95% CI		Q	df	p-value
Design	Cross-over RCT	7	0.196	[-0.054,0.446]		0.3	1	0.568
		5	-0.013	[-0.685,0.659]				
Continuous moderator	Level	No. of studies	β	95% CI	I2%	Q	df	p-value
Age, years	12.3 to 22.21	12	-0.018	[-0.082,0.046]	61.3	0.3	1	0.582
Boys, %	33.3 to 57.1	12	-0.015	[-0.046,0.015]	50.2	1.0	1	0.327
Duration, min	10 to 60	12	-0.005	[-0.011,0.020]	54.8	0.3	1	0.577
Intensity, bpm	123 to 181	10	-0.004	[-0.012,0.019]	62.2	0.2	1	0.627
Dose (min $\times$ bpm)	1486 to 9680.4	10	0.000	[-0.000,0.000]	58.9	0.2	1	0.628
Inhibition								
Categorical moderator	Level	No. of studies	Cohen <i>s d</i>	95% CI		Q	df	p-value
Design	Cross-over RCT	15	0.312	[0.099,0.525]		0.0	1	0.866
		20	0.334	[0.189,0.480]				
Type of control group	Waiting list	3	0.089	[-0.316,0.494]		1.3	1	0.252
	Rest	32	0.338	[0.207,0.469]				
Continuous moderator	Level	No. of studies	B	95% CI	I2%	Q	df	p-value
Age, years	12.6 to 26	35	-0.011	[-0.041,0.018]	39.6	0.6	1	0.448
Boys, %	10 to 100	33	-0.003	[-0.008,0.002]	41.6	1.4	1	0.238
Duration, min	5 to 60	35	-0.001	[-0.012,0.009]	39.8	0.1	1	0.800
Intensity, bpm	94.9 to 188	21	-0.003	[-0.008,0.003]	0.0	0.9	1	0.342
Dose (min $\times$ bpm)	940 to 9680.4	21	0.000	[-0.000,0.001]	0.0	0.	1	0.642
CHRONIC INTERVENTIONS								
Attention								
Continuous moderator	Level	No. of studies	β	95% CI	I2%	Q	df	p-value
Age, years	12.4 to 26	11	0.016	[-0.037,0.070]	71.7	0.4	1	0.547
Boys, %	32.1 to 70.7	10	0.018	[0.003,0.034]	51.2	5.3	1	0.021
Duration, weeks	1 to 26	11	-0.029	[-0.062,0.004]	68.7	2.9	1	0.087
Frequency, days/week	2 to 5	11	-0.138	[-0.345,0.070]	68.7	1.7	1	0.194
Working memory								
Continuous moderator	Level	No. of studies	β	95% CI	I2%	Q	df	p-value
Age, years	12.45 to 26	14	-0.000	[-0.066,0.066]	71.2	0	1	0.995
Boys, %	14.7 to 100	14	0.014	[0.001,0.027]	64.2	4.5	1	0.033
Duration, weeks	6 to 17	14	0.013	[-0.077,0.104]	71.3	0.1	1	0.772
Frequency, days/week	2 to 5	14	0.147	[-0.155,0.448]	70.0	0.9	1	0.400
Dose, min per week	90 to 360	12	0.001	[-0.001,0.003]	39.2	1.0	1	0.329
Load, min per intervention	540 to 4320	12	0.000	[-0.000,0.000]	36.6	1.6	1	0.202

bpm, beats per minute; RCT, Randomized controlled trial.

the observed associations between the chronic physical activity interventions and cognitive outcomes may be overestimated.

Discussion

This meta-analysis investigated the effects of acute and chronic physical activity interventions on cognitive outcomes and academic performance in adolescents and young adults. Results of the meta-analysis showed that acute physical activity interventions have a positive effect on attention, processing speed and

inhibition. Furthermore, the meta-analysis showed that chronic physical activity interventions have a positive effect on processing speed, attention, cognitive flexibility, working memory and language, where the largest effect was found on working memory.

Interpretation

Most of the conducted meta-analyses showed large or medium heterogeneity between the individual studies' effect sizes. Therefore, the findings should be interpreted with caution.

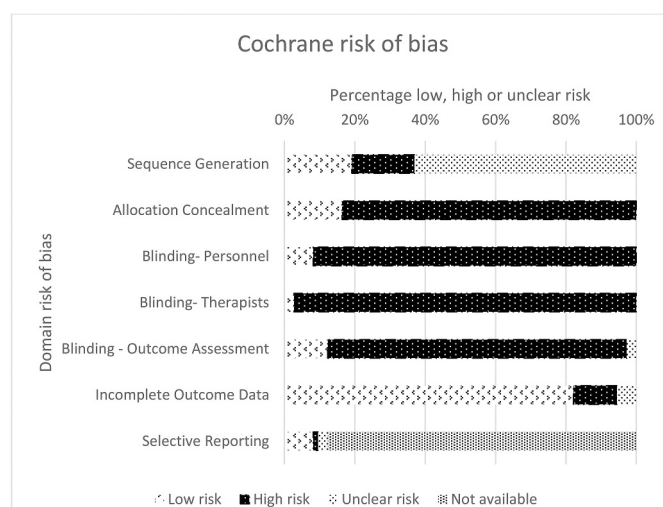


Figure 3. Analysis of the risk of bias in included studies in accordance with the cochrane collaboration guidelines.

We investigated potential sources of heterogeneity by performing several meta-regression analyses and subgroup analyses. Some remarkable findings and possible sources of heterogeneity will be discussed.

An interesting finding of this meta-analysis is the beneficial effect of chronic physical activity interventions on cognitive outcomes and especially on the core domains working memory and cognitive flexibility. Our findings confirm the results of Rathore & Lom (2017) who also found positive significant effect sizes for working memory and those of De Greeff et al. (2018) who found positive results for working memory and cognitive flexibility, but not in inhibition. However, our findings differ from the meta-analytic results of Xue et al. (2019), who showed positive effects on inhibition, but not on working memory or cognitive flexibility and of Alvarez-Bueno et al. (2017), who showed positive effects on inhibition, but not on working memory or cognitive flexibility. Overall, the previous meta-analytic studies were inconsistent in their findings. Probably, these divergent findings have emerged because these meta-analyses included mostly pre-adolescent children or older adults and almost no adolescents or early adulthood subjects. The transition from childhood to adulthood starts with physical changes and hormonal changes. These changes start in late childhood or in early adolescence, also referred to as early puberty, and continue into early adulthood (Malina et al., 2004). In the later-puberty, rapid development of the prefrontal cortex takes place which may make this structure especially sensitive to the effects of interventions, like physical activity interventions, compared to other developmental stages (Lebel et al., 2008). Moreover, the transition from childhood into adulthood is characterised by a marked decrease in physical activity and an increase in sedentary behaviour (Corder et al., 2017; Hardy et al., 2007; Kimm et al., 2000). The low levels of physical activity in adolescents might make physical activity interventions result in relatively large increases in physical activity in later-puberty than in pre-adolescent children. Concluding the current meta-analysis is the first to include a substantial number of studies investigating the effects of chronic physical activity interventions in adolescents and

young adults which might explain the different conclusion reached as compared to previous reviews.

Another interesting finding was that chronic physical activity interventions were found to have a moderately sized beneficial effect on academic performance. Further analyses showed that a chronic intervention can positively affect language, but not grade point average or mathematics. This is slightly different from a previous meta-analysis, which showed positive effects on science, including mathematics, but not on language or grade point average (Spruit et al., 2016). In another meta-analysis, positive effects on language as well as on mathematics were found (Álvarez-Bueno, Pesce, Caverio-Redondo, Sánchez-López, Garrido-Miguel et al., 2017). However, in that meta-analysis mainly preadolescent children were included. Only 3 out of 25 studies were conducted in similar age ranges as included in the current meta-analysis (12–30 years). While in the age range of 12–18 years a lot of behavioural changes take place that stay present in adults (Cluskey & Grobe, 2009). If more studies are conducted in adolescence a more clear effect with possibly less heterogeneity will be visible in this age. Heterogeneous results between studies in this meta-analysis can possibly be explained by the fact that mostly school grades were used as outcome measure instead of standardized tests. School grades are less objective and comparable with other studies than standardized tests, because they depend on the topic discussed in that period and sometimes the grade is awarded subjectively by the teacher. Furthermore, it should be noted that academic performance was only measured in adolescents and not in young adults, so findings cannot be generalized to young adulthood. Moreover, the oldest mean age was 15.3 years. In sum, findings for the effects of chronic physical activity interventions on the subdomains of academic performance are inconsistent and more research is warranted, especially with standardized tests.

This meta-analysis showed significant effect sizes after a chronic intervention but not after an acute intervention on cognitive flexibility and working memory. While chronic interventions showed a large effect size, acute interventions yielded small or non-significant effects, suggesting that only chronic physical

activity interventions may affect cognitive flexibility and working memory. One possible explanation for this difference in effect sizes is that different underlying mechanisms operate in acute and chronic interventions. It is suggested that physical activity, for example, facilitates working memory by increasing the efficiency of evaluating the stimulus (Chang et al., 2013). Underlying processes that could increase this efficiency are neurogenesis and synaptogenesis, which are related to chronic interventions (Hillman et al., 2015). In the review of Gomez-Pinilla & Hillman (2013) brain-derived neurotrophic factor (BDNF) is suggested to be an important initiator of synaptic plasticity. Exercise influences the production of BDNF in the area critical for learning and memory. After acute interventions, BDNF levels are increased for a short time period and could explain increased levels of arousal, attention and effort, which positively influences the performance on cognitive tasks (Kashihara et al., 2009; Tomporowski, 2003). However, after a chronic intervention BDNF levels stay increased and therefore have a structural effect on neurons, like neurogenesis and synaptic plasticity. It seems that the underlying process like synaptogenesis, neurogenesis and synaptic plasticity are the underlying mechanisms of improved cognitive flexibility and working memory.

A remarkably large difference between acute and chronic physical activity interventions was found on working memory. Sample and study characteristics might explain the discrepant findings for this difference in effect size. Sample characteristics sex and age were tested as possible moderators. Sex did differ between the two types of studies: in chronic interventions, effects were stronger for studies with a high percentage of boys compared to low percentage of boys, while no difference in the effects for high and low percentage of boys was found in acute studies. This may have been due to differences in compliance (boys may have been more active in chronic studies) or stage of maturation. Moreover, during puberty physical activity patterns change, earlier in girls than in boys (Bacil et al., 2015). Due to the difference in time onset of physical activity changes and biological differences, boys have probably a better maximum oxygen uptake and are more active during and outside the intervention time, which will lead to a more pronounced effect on cognition in boys compared to girls. However, information about adherence and compliance in the intervention and the maturation was not always reported in the studies and therefore we cannot say whether this is the case. Therefore, it is suggested for future studies to measure compliance, adherence and maturation of boys and girls when conducting an intervention study. Next to sex, age was also tested as a moderator, however age had similar effects in acute versus chronic studies, and could therefore not explain the difference between chronic and acute studies. The used measurement instrument is an example of a study characteristic that could explain the discrepant findings. However, the conflicting findings do not seem to be related to differences in the measures used to assess working memory: for both acute as well as chronic intervention studies, similar instruments were used to measure working memory in the included studies. The majority of the studies used the Digit Span test or the N-back test. Therefore, it seems unlikely that the type of measurement instrument has contributed to the different results.

Furthermore, the type of interventions that were delivered seem to differ between acute and chronic studies. In acute intervention studies only aerobic or resistance exercises were given, but in chronic studies also yoga and cognitively challenging exercises were given besides or instead of the aerobic exercises. In cognitively challenging interventions the motor-cognition network might play a role in the improvement of the executive functions. This network is supported by the recruitment of neural regions during performance of motor tasks, which are typically associated with cognitive operations such as the dorsolateral prefrontal cortex and the neo-cerebellum (Ludyga et al., 2016). During physical activity, cognition may or may not be challenged by performing (increasingly) difficult movements or by increasing rules or the number of objects to be handled in an exercise (Tomporowski et al., 2015). We assume that in particular these characteristics of exercises challenge the motor-cognition network and this might explain the different results found in working memory. There were too few studies to examine whether cognitively challenging interventions have a different effect on executive functions compared to other types of physical activity interventions, but results of meta-analyses in preadolescent children support this hypothesis (De Greeff et al., 2018; Vazou et al., 2019). In sum, chronic intervention studies seem more promising to improve working memory than acute interventions in adolescents, however, it is not clear what causes this difference.

Findings in our meta-regression revealed that, in acute intervention studies, intervention effects were smaller with longer duration for attention and cognitive flexibility. Between studies, duration of interventions varied between 5 and 60 minutes. This finding suggests that a short bout of physical activity is more effective than longer bouts of physical activity to improve cognitive functioning. However, studies did not investigate the optimal intervention length, nor the persistence of the observed beneficial effects on cognitive functions. In the meta-analysis of Ludyga et al. (2016) it was suggested that short aerobic exercise bouts of moderate intensity restore cognitive resources, a finding that is in line with our results. Furthermore, it could be that with increasing intervention duration, participants get more exhausted, which in turn would have a negative effect on task performance after a long intervention session. In sum, it seems that a short acute physical activity intervention is more efficient than a long bout of acute physical activity intervention to improve cognitive functions. Further research is needed to investigate the optimal duration of an acute physical activity intervention and to investigate how long positive effects remain after an acute bout of physical activity.

Strengths and limitations

One strength of this meta-analysis is the inclusion of both adolescents and young adults, since these age periods reflect a period of rapid maturation of the brain, with most prominent changes in the prefrontal cortex (Lebel et al., 2008). Moreover, the transition to adulthood often concurs with life changes, that influence health related behaviours, like behaviour changes in a new environment, with changing social contacts and support (Cluskey & Grobe, 2009; Horn et al., 2008). Another strength is the inclusion of studies with a RCT or cross-over

design only and the exclusion of observational and cross-sectional studies. This strict inclusion increases the reliability of the causal effects of physical activity interventions on cognitive functions and academic performance. Finally, we conducted a risk of bias assessment to get more insight in the methodological quality of the included studies. A limitation of this review was that we could not perform all subgroup-analyses and meta-regression analyses due to the small number of studies available. Furthermore, for chronic intervention studies, we were neither able to perform meta-regression analyses to study the effects of total load (intensity $\times$ dose) nor to study the effects of improvement on physical fitness, because most studies did not report intensity levels. Another limitation is the possibility of publication bias in the studies investigating chronic physical activity interventions. Lastly, cognitive outcomes were measured across studies using a wide variety of measurement instruments, which could have contributed to the heterogeneity in the meta-analyses.

Conclusion

In conclusion, this meta-analysis demonstrates that there are positive effects of physical activity interventions on cognitive outcomes in both acute and chronic studies in adolescents and young adults. Furthermore, this meta-analysis demonstrates a positive effect of physical activity on academic performance within the language domain, but not on grade point average or mathematics, in adolescents. Additionally, this study shows that in acute interventions shorter bouts of exercise appear to be more effective than longer bouts of exercise for improving cognitive outcomes. Finally, both acute and chronic interventions seem promising to improve cognitive outcomes and academic performance in adolescents and young adults. However, chronic physical activity interventions seem to have larger effect sizes on a broader range of cognitive outcomes than acute physical activity interventions. So in practice it is recommended to implement chronic physical activity interventions instead of acute physical activity interventions when possible.

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ORCID

Barbara Franca Haverkamp  <http://orcid.org/0000-0003-3776-0604>
Rikstje Wiersma  <http://orcid.org/0000-0001-7577-0606>

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Appendices

Appendix A. Search Strategy MEDLINE

("Young Adult"[Mesh] OR "Adolescent"[Mesh] OR young adult*[tiab] OR adolescen*[tiab] OR youth[tiab] OR teens[tiab] OR teenager*[tiab] OR girl*[tiab] OR boy*[tiab] OR pubert*[tiab] OR ((high[tiab] OR middle[tiab] OR secondary[tiab]) AND school*[tiab]) OR (young*[tiab] AND (people[tiab] OR person*[tiab])))

AND

("Physical Education and Training"[Mesh] OR "Motor Activity"[Mesh:NoExp] OR "Exercise"[Mesh] OR "Athletic Performance"[Mesh] OR "Exercise

Therapy"[Mesh] OR "Exercise Movement Techniques" [Mesh] OR physical activ*[tiab] OR yoga [tiab] OR ((physical[tiab] OR aerobic[tiab] OR chronic [tiab] OR acute[tiab]) AND exercis*[tiab]) OR ((exercis*[tiab] OR fitness[tiab]) AND (training[tiab] OR intervention*[tiab] OR program*[tiab])) OR movement intervent*[tiab] OR movement program*[tiab] OR strength training [tiab] OR circuit training[tiab])

AND

("Executive Function"[Mesh] OR "Attention"[Mesh] OR "Cognition"[Mesh: NoExp] OR "Problem Solving"[Mesh] OR "Inhibition (Psychology)"[Mesh] OR "Memory"[Mesh] OR "Academic Performance"[Mesh] OR executive function* [tiab] OR executive control*[tiab] OR attention[tiab] OR cognit*[tiab] OR inhibition[tiab] OR working memory[tiab] OR planning[tiab] OR set shift*[tiab] OR processing speed[tiab] OR processing time[tiab] OR ((academic[tiab] OR school [tiab]) AND (achiev*[tiab] OR perform*[tiab] OR skill*[tiab] OR competen*[tiab] OR behavio*[tiab] OR engagement[tiab])) OR academic outcome*[tiab] OR learning outcome*[tiab] OR language[tiab] OR spelling[tiab] OR reading comprehension*[tiab] OR math*[tiab] OR science[tiab] OR grade point*[tiab])

AND

("Controlled Clinical Trial" [Publication Type] OR randomi*[tiab] OR randomly[tiab] OR control group*[tiab] OR groups[tiab] OR trial[ti] OR control condition*[tiab])

Appendix B1. Study characteristics of acute physical activity interventions

Author	Age, years (M ± SD)	Study design	In- and exclusion criteria	Group (n)	Duration (min)	Intensity	Type of control and intervention	Outcome measures and instruments (dependent variable)
Akatsuka et al. (2015)	19.8	cross over	Inclusion criteria: right handed. Exclusion criteria: neurological disease	CG (10)	20	NR	Rest	Inhibition: Go-no go task (reaction time and accuracy)
Aquirre-Loaiza et al. (2019)	20.7 ± 2.5	RCT	Exclusion criteria: score >30 on the Beck Depression Inventory, cardiovascular problems	EG (10) CG (30)	15 45	50% oxygen intake NR	Aerobic Rest	Inhibition: Stroop (seconds); Cognitive flexibility: Trail making test (seconds)
Aquirre-Loaiza et al. (2019)	21.6 ± 1.8	RCT	Exclusion criteria: score >30 on the Beck Depression Inventory, cardiovascular problems	EG (30) CG (27)	45 30	HRmean 137 bpm NR	Aerobic Rest	Inhibition: Stroop (seconds); Cognitive flexibility: Trail making test (seconds)
Basso et al. (2015)	22.21 ± 4.14	RCT	Exclusion criteria: major surgery within the prior 6 months; a past or present history of drug or alcohol abuse, a diagnosed psychiatric or neurological condition, medication known to affect cognition, or unable to safely participate in an aerobic exercise program.	EG (26) CG (42)	30 60	HRmean 143 bpm NR	Aerobic Rest	Inhibition: Stroop task (interference score); Working Memory: Symbol Digit
Benzing et al. (2016)	14.51 ± 1.08	RCT	Exclusion criteria: neurological, developmental, or medical condition that would affect the subject integrity or study results	EG (21)	15	HRmean 82 bpm	Rest	Modalities Test (number of correct answers), Digit Span Test (number of correct answers; total of forward and backward); Cognitive flexibility: Trail Making Test (seconds to complete trial B)
Browne et al. (2016)	13 ± 1.8	Cross over	Inclusion criteria: available to attend the assessment, to be physically active in extracurricular sports, meet the criteria of the PAR-Q, to be classified as "pubertal" (Tanner stages 2–4). Exclusion criteria: physical or intellectual disabilities, or clinical, neuromotor, psychological or cognitive contraindications	CG (20) EG (20)	15 30	HRmean 152 bpm HRmean 81 bpm	Aerobic Rest	Inhibition: D-KEF (number of created objects); Cognitive flexibility: D-KEF (number of created objects)
Budde et al. (2008)	16.6 ± 0.8	RCT	Exclusion criteria: dyslexia or BMI >25	CG (52)	10	HRmean 122 bpm	Some activity	Attention: D2-test
Budde et al. (2010)	14.4 ± 0.5	RCT	Exclusion criteria: dyslexia, BMI >25, mental or physical impairments or psychoactive substances	EG (47) CG (21)	10 12	HRmean 122 bpm HRmean 86 bpm	Cognitive Rest	engagement Working Memory: Letter Digit Span (number of correct answers)
Chang and Etner (2009)	26.0 ± 3.2	RCT	Inclusion criteria: meet the criteria of PAR-Q	EG1 (18) EG2 (20) CG (16)	12 12 30	HRmean 124 bpm HRmean 160 bpm HRmean 79 bpm	Aerobic Aerobic Rest	Inhibition: Stroop (seconds); Attention: Paced Auditory serial addition task (correct answers in trial 4)
Chang et al. (2011)	22.3 ± 2.0	RCT	Inclusion criteria: meet the criteria of PAR-Q	EG1 (16) EG2 (16) EG3 (17) CG (22)	30 30 30 30	HRmean 95 bpm HRmean 116 bpm HRmean 136 HRmean 75 bpm	Resistance Resistance Resistance Rest	Planning: Tower of London (execution time, seconds)
Coles et al. (2008)	22.2 ± 1.6	cross over	Exclusion criteria: contradiction for maximal exercise	EG (20) CG (18)	30 40	HRmean 154 bpm NR	Aerobic Rest	Cognitive flexibility: Visual shift task of Kramer (response time)

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Author	Age, years (M ± SD)	Study design	In- and exclusion criteria	Group (n)	Duration (min)	Intensity	Type of control and intervention	Outcome measures and instruments (dependent variable)
Cooper et al. (2012)	13.3 ± 0.3	cross over	Inclusion criteria: good health following the health screen questionnaire	EG (18) CG (45) EG (45)	40 10 10	HRmean 141 bpm NR HRmean 172 bpm	Aerobic Rest Aerobic	Working Memory: Sternberg paradigm (reaction time); Inhibition: Stroop (seconds)
Cooper et al. (2016)	12.6 ± 0.6	cross over	Inclusion criteria: good health following the health screen questionnaire	CG (44) EG (44)	10 10	HRmean 90 bpm HRmean 181 bpm	Rest Aerobic	Working Memory: Corsi Block test (mean of three longest correct sequences), Digit Symbol Substitution Test (number of correct responses in 45 s); Inhibition: Stroop (seconds)
Du Rietz et al. (2019)	21.5 ± 2.52	cross over	Inclusion criteria: meet the criteria of PAR-Q. Exclusion criteria: cardiovascular, lung or metabolic disease, BMI>30, bone or joint problems, epilepsy, or asthma.	CG (26)	30	HR end session 75 bpm	Rest	Inhibition: Go-no go task, Flanker task; Processing speed: fast task
Griffin et al. (2011)	22.0 ± 2.0	CT	Inclusion criteria: be able to participate in PE class	CG (13) EG (29) CG (30)	30 NR 30	NR NR NR	Rest Aerobic Rest	Inhibition: Stroop
Guzman and López-García (2016)	21.9 ± 2.7	RCT	Exclusion criteria: contradiction of moderate aerobic exercise. Inclusion criteria: be physical active for at least 4 hours a week	EG (62)	30	60–70% Hmax	Aerobic	Attention Vienna Test system
Hwang et al. (2016)	23.6 ± 3.0	RCT	Exclusion criteria: psychotic disorders or neural conditions, medication or tobacco use	CG (29)	20	HRmean 64 bpm	Rest	Inhibition: Stroop; Working Memory: Trail Making test
Hwang and Lu (2018)	21.36 ± 2.11	RCT	Exclusion criteria: cardiovascular or neurological diseases, attentional disorders, physical disabilities, tobacco users, or never played a video game	EG (29) CG (25)	20 30	HRmean 158 bpm NR	Aerobic Rest	Working Memory: Delayed match memory task; Attention: psychomotor vigilance test
Jaffery et al. (2018)	21.4 ± 0.5	RCT	Exclusion criteria: smoking, caffeine or exercise 6 hours before measurements.	EG (25) CG (22) EG (22)	30 10 5	HRmean 125 bpm NR HRmean 116 bpm	Aerobic Rest Aerobic	Cognitive flexibility: Trail making test (score on B-trial)
Lambourne et al. (2010)	21.1 ± 1.7	cross over	Inclusion criteria: physical exercise at least 3 times a week, filled in the medical history questionnaire	CG (19)	40	HRmean 84 bpm	Rest	Attention: PASAT
Lambourne (2012)	21.1 ± 0.9	cross over	Inclusion criteria: PA at least 3 days a week. Exclusion criteria: intake of caffeine or medication on the day of measurement	EG (19) CG (16) EG (16)	40 25 35	HRmean 143 bpm NR 90% ventilary threshold	Aerobic Rest Aerobic	Working Memory: Operation Span Task
Ludyga, Pühse et al. (2019)	14.0 ± 0.7	RCT	Inclusion criteria: normal or corrected to normal vision and the ability to fully engage in PE. Exclusion criteria: medication for mental disorders or injuries of the hand	CG (28)	20	HRmean 88 bpm	Rest	Inhibition: Flanker task
Mezcua-Hidalgo et al. (2019)	14.06 ± 1.29	RCT	Exclusion criteria: physical limitations or medical contradictions to carry out intense physical exercise. Participating in an official sport club or competitive sports	EG1 (34) EG2 (32)	20 20	HRmean 143 bpm HRmean 154 bpm	Aerobic Aerobic	Memory: ad hoc test; Attention: D2-test
Moore et al. (2012)	22	RCT	Exclusion criteria: neurological or cardiovascular disease, medication influencing nervous system function, or any contradiction to vigorous exercise. Inclusion criteria: normal or corrected to normal vision	CG (81) EG (77) CG (15) EG (15)	20 20 60 60	HRmean 91 bpm HRmean 157 bpm NR 90% ventilary threshold	Some activity Aerobic Rest Aerobic	Processing speed: Visual discrimination performance

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Author	Age, years (M ± SD)	Study design	In- and exclusion criteria	Group (n)	Duration (min)	Intensity	Type of control and intervention	Outcome measures and instruments (dependent variable)
Murray and Russoniello (2012)	20.86 ± 2.82	RCT	NR	CG (60)	30	NR	Rest	Working Memory: Trail making test; Processing speed: reaction time (seconds)
Palmieri et al. (2018)	22 ± 3	cross over	Exclusion criteria: cardiovascular, renal, pulmonary, neurological or metabolic diseases. Smokers, a history of concussions, exercise-induced syncope or visual impairments	EG (60) CG (35) EG (35)	30 30 30	75% HRmax NR NR	Aerobic Rest Resistance	Inhibition: Flanker task; Working Memory: N-back test, Memory: Memory recognition task
Peruyero et al. (2017)	16.39 ± 0.68	cross over	NR	CG (44)	20	NR	Rest	Inhibition: Stroop
Pontifex et al. (2009)	20.2 ± 0.3	cross over	Inclusion criteria: normal or corrected to normal vision and no neurological diseases	EG1 (44) EG2 (44) CG (21)	30 30 30	light moderate HRmean 68 bpm	Aerobic Aerobic Rest	Working Memory: Sternberg task
Prashant (2020)	20.69 ± 1.234	RCT	Inclusion criteria: No auditory or visual impairment. All the participants underwent cognitive function tests for the 1st time.	EG1 (21) EG2 (21) CG (50)	30 30 10	HRmean 162 bpm HRmean 123 bpm NR	Aerobic Resistance Rest	Processing speed: Reaction time (visual and auditory)
Schwarck et al. (2019)	23.33 ± 3.23	RCT	Inclusion criteria: physically active (<3 sessions a week), normal BMI, right-hand dominant and free of any cardiovascular, neurological and pulmonary disorder. Exclusion criteria: colour-blindness and uncorrected vision.	EG (50)	5	NR	Aerobic	Inhibition: Stroop (seconds); Attention: D2-test; Cognitive flexibility: Trailmaking test
Sipaviciene et al. (2012)	19.5 ± 1.5	RCT	NR	CG (30)	20 vs 90	NR	NR	Attention: Attention concentration test; Processing speed: Reaction time test
Sperlich et al. (2018)	22 ± 2	cross over	Exclusion criteria: routine experience with HIIT	EG (60) EG (60) CG (12)	17 85 6	NR NR HRmean 75 bpm	Aerobic Aerobic Rest	Inhibition: Stroop
Takahashi et al. (2019)	20.9 ± 0.89	Cross over	Inclusion criteria: free of any cardiopulmonary and metabolic disease and visual disorder. No alcohol use or strenuous physical activity 24 hours before experiment, no smoking, food or caffeine consumption 2 hours before experiment	EG (12) CG (20) EG1 (20) EG2 (20)	6 10 10 10	HRmean 166 bpm HR peak: 74 bpm HR peak: 160 bpm HR peak: 159 bpm	Aerobic Rest Aerobic Cognitive	Inhibition: Stroop engagement
Tine (2014)	17–21	RCT	Exclusion criteria: learning disabilities	CG (39) EG (46) CG (78)	12 12 12	NR 70–80% HRmax NR	Rest Aerobic Rest	Language: reading comprehension task Attention: D2-test
Tine and Butler (2012)	12.3	RCT	Exclusion criteria: reduced priced lunch	EG (78)	12	70–80% HRmax	Aerobic	

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Author	Age, years (M ± SD)	Study design	In- and exclusion criteria	Group (n)	Duration (min)	Intensity	Type of control and intervention	Outcome measures and instruments (dependent variable)
Tsai et al. (2016)	22.56 ± 1.81	CT	Inclusion criteria: right handed, normal or correct to normal vision, non-smoker. Exclusion criteria: neurological disorders, cardiovascular diseases, depression, cognitive impairment, or medication that influences nervous system functioning	CG (20) EG1 (20) EG2 (20)	47 30 30	NR >75% ventilary threshold <45% ventilatory threshold	Rest Aerobic Aerobic	Cognitive flexibility: task-switching test
Tsai et al. (2014)	22.35 ± 1.86	CT	Inclusion criteria: right handed, normal or correct to normal vision, non-smoker. Exclusion criteria: neurological disorders, cardiovascular diseases, depression, cognitive impairment, or medication that influences nervous system functioning, strenuous exercise or alcohol intake 24 hours before measurement or caffeine 3 hours before measurement	CG (20) EG1 (20) EG2 (20)	47 30 30	NR >75% ventilary threshold <45% ventilatory threshold	Rest Aerobic Aerobic	Inhibition: visuospatial attention paradigm
Tsorbatzoudis et al. (1998)	20.0 ± 3.2	CT	NR	CG (11)	10 vs 35	NR	Rest	Attention: Vienna Test system
Tsukamoto et al. (2017)	22.9 ± 1.4	cross over	Inclusion criteria: right handed. Exclusion criteria: neurological, cardiovascular, or pulmonary diseases, colour blindness or abnormal vision	EG1 (12) EG2 (24) CG (12)	5 35 17	HRmean 178 bpm HRmean 167 bpm HRmean 66 bpm	Aerobic Aerobic Rest	Inhibition: Stroop
van den Berg et al. (2018)	12.3 ± 0.6	cross over	Exclusion criteria: a medical condition that could affect concentration or memory	EG1 (12) EG2 (12) CG (99)	17 17 20	HRmean 105 bpm HRmean 142 bpm NR	Resistance Resistance Rest	Working Memory: N-back test; Attention: ANT
Vonk et al. (2019)	23 ± 2	Cross over	Inclusion criteria: PARQ. Exclusion criteria: musculoskeletal disorders, concussion in the last year, epilepsy or taking medications that would alter heart rate or blood pressure.	EG (99) CG (22)	20 30	HRmean 135 bpm HRmean 92 bpm	Aerobic Rest	Inhibition: Stroop
Wang et al. (2015)	22.67 ± 2.55	RCT	Inclusion criteria: right handed, normal or corrected to normal vision with normal colour vision, meet the criteria of PAR-Q	CG (13)	30	HRmean 83 bpm	Rest	Cognitive flexibility: Wisconsin card sorting test
Whyte et al. (2014)	21.25 ± 1.29	RCT	Exclusion criteria: colour blindness, injury, previously concussed, taking medication that might affect neurocognitive ability. Intake of alcohol or caffeine 24 hours before measurements	EG (14) CG (20) EG (20)	30 10 10	HRmean 151 bpm NR HRmax 188 bpm	Aerobic NR Aerobic	Inhibition: Stroop; Working Memory: Symbol Digit Modality test
Zhou & Qin. (2019)	20.07 ± 1.27	RCT	Inclusion criteria: between 18 and 26 years, right-handedness, normal or corrected-to-normal vision and colour perception, a BMI < 25, no psychiatric, neurological disorders, cardiovascular disease or physical disability. Exclusion criteria: > 3× moderate exercise intensity per week	CG (36) EG (36)	25 25	Rest HRmean 133 bpm	Rest Aerobic	Inhibition: Stroop (ms incongruent trials)
Zimmer et al. (2016)	23.82 ± 3.64	RCT	Exclusion criteria: BMI < 18 or > 30, cardiopulmonary, neurological, metabolic or psychiatric disease. Intake of medication or illegal drugs, or acute infection, pregnancy or extensive physical training in previous 2 weeks	CG (31) EG1 (30) EG2 (30) EG3 (30)	35 35 35 35	NR 45–50% HRmax 65–70% HRmax 85–90% HRmax	Some activity Aerobic Aerobic Aerobic	Inhibition: Stroop

n: number of participants; HRmean: mean heart rate during the intervention; bpm: beats per minute; PAR-Q: physical activity readiness questionnaire; NR: not reported; RCT: Randomized controlled trial; CT: controlled trial; EG: experimental group; CG: control group; BMI: Body mass index.

Appendix B2. Study characteristics of chronic physical activity interventions

Author	Age, years (M± SD)	Study design	In- and exclusion criteria	Group (n)	Duration (weeks)	Dose (min/week)	Intensity	Type of control and intervention	Outcome measures and instruments; dependent variables
Arday et al. (2014)	13 ± 0.81	RCT	Exclusion criteria: personal history of cardiovascular disease, cognitive dysfunction, or not being able to actively participate in PE classes Inclusion criteria: 9 th or 10 th grade in a public high school	CG (17)	17	110	HRmean 116 bpm	Some activity	GPA, mathematics, language: school grades
Butzer et al. (2015)	NR	RCT		EG1 (20) EG2 (17) CG (51)	17 17 12	220 220 85	HRmean 129 bpm HRmean 147 bpm NR	Aerobic Aerobic Some activity	GPA: school grades
Costigan et al. (2016)	15.8 ± 0.6	RCT	NR	EG (44) CG (22)	12 8	85 NR	NR NR	Yoga Some activity	Working Memory: Trail making test (time to complete trial B)
Duarte et al. (2020)	12–14 years	RCT	Inclusion criteria: able to follow instructions. Exclusion criteria: hyperactivity disorder and attention deficit previously diagnosed, and students with previous experience of the practice of Qigong. Inclusion criteria: All students who were cleared for PE class	CG (22) EG (22)	4 4	10 10	NR NR	Aerobic Resistance and Aerobic Rest Yoga	Attention: D2 test
Hagins & Rundle (2016)	15.3 ± 1.0	RCT		CG (64)	40	90	NR	Some activity	GPA: School grades
Heisz et al. (2017)	20.71 ± 2.73	RCT	Exclusion criteria: more than 1 hour of vigorous exercise a week	EG (48) CG (32)	40 6	90 60	NR NR	Yoga Some activity	Memory: mnemonic similarity task (accuracy)
Jeon & Ha (2017)	15.18 ± 0.61	RCT	Exclusion criteria: history of physical illness or participating in any sport activities outside PE	EG (34) CG (10)	6 12	60 120	NR light	Aerobic Some activity	Working memory: Digit span (total score forward and backward)
Johann et al. (2016)	23.5 ± 3.2	RCT	Exclusion criteria: colour blindness, achromatopsia, injuries preventing physical activity, chronic physical or psychiatric diseases, psychotropic medication, or blood pressure medication assessed by a biographic questionnaire	EG1 (10) EG2 (10) EG3 (10) CG (24)	12 12 12 6	172 132 104 NR	HRmean 121 bpm HRmean 142 bpm HRmean 162 bpm NR	Aerobic Aerobic Aerobic Some activity	Inhibition: Flanker task (difference in congruent and incongruent score); Cognitive flexibility: Task switching (reaction time and accuracy); Fluid Intelligence: Raven advanced progressive matrices (number of correct answers); Working memory: Counting span (number of correct responses)
Kauts & Sharma (2009)	age range 14–15 years	RCT	NR	EG1 (32) EG2 (35) CG (137)	6 6 7	90 90 NR	NR 50–70 max pulse rate NR	Cognitive engagement Aerobic Some activity	Mathematics, Social studies and Science: Standardized tests
Lennehan et al. (2013)	Age range 18–34 years	RCT	Inclusion criteria: students who graduated from basic military course and took part in US Air Force School of Aerospace Medical technical training	EG (164) CG (18) EG (23)	7 6 6	300 NR NR	NR NR NR	Yoga Some activity Aerobic	Working memory: n-back task (reaction time and accuracy); Attention: visual vigilance task (percentage correct answers), dichotic listening task (percentage correct answers)

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	Age, years (M ± SD)	Study design	In- and exclusion criteria	Group (n)	Duration (weeks)	Dose (min/ week)	Intensity	Type of con- trol and intervention	Outcome measures and instruments; dependent variables
LudyaGerber, Kamijo (2018)	12.45 ± 0.7	RCT	Inclusion criteria: right handed, normal or corrected-to-normal vision. Exclusion criteria: attending special education services related to cognitive impairments or attentional disorders, or receiving pharmacotherapy for mental disorders, colorblindness, or medical condition which increase health risks during exercise	CG (16) EG (17)	8 8	100 100	NR HRmean 135 bpm	Sedentary Aerobic and cognitive engaging	Working memory: Sternberg (reaction time and accuracy)
Ludya et al. (2018)	12.45 ± 0.7	RCT	See in- and exclusion criteria Ludya, Gerber, Kamijo et al. (2018)	CG (16) EG (17)	8 8	100 100	NR HRmean 135 bpm	Sedentary Combination aerobic and cognitively	Inhibition: Stroop (reaction time and accuracy)
challenging Ludya, Köchli et al. (2019)	12.5 ± 0.83	RCT	Inclusion criteria: right handed, normal or corrected to normal vision. Exclusion criteria: colour blindness, attentional disorders, injuries or diseases that impose an increased health risk during exercise performance, being under pharmacological treatment for any mental disorder.	CG (16) EG (19)	8 8	100 100	NR HRmean 135 bpm	Rest Combination aerobic and cognitively	Inhibition: Stroop challenging
Matthews et al. (2016)	22.1 ± 2.8	RCT	Exclusion criteria: injury that could interfere with the intervention. Inclusion criteria: participate in PA at least 3 times a week	CG (11) EG (11)	4 4	NR 180	NR NR	Some activity Coordination	Cognitive flexibility: Wisconsin Card Sorting Test (perspective errors)
Pinto-Escalona & Martínez-de-Quel (2019)	13.6 ± 0.7	RCT	Inclusion criteria: secondary grade of secondary education of state-subsidised private school	CG (60)	1	50	NR	CG: Rest	Attention: Strengths and difficulties questionnaire (item 15, 21, 25); Academic Performance: language (standardized test)
Purohit & Pradhan (2017)	12.8 ± 1.4	RCT	Inclusion criteria: orphans between 11–16 years and apparently healthy without any chronic illness, physical or mentally handicap	EG (56) CG (32)	1 12	50 NR	NR NR	EG: Aerobic Some activity	Inhibition: Stroop (number of correct responses in 45 s); Working memory: Digit Span task (total score forward and backward), Digit symbol substitution test (number of correct responses); Attention: Trail making test time to complete Trail A); Cognitive flexibility: Trail making test (time to complete Trail B)
Sharma et al. (2015)	13.94 ± 1.42	RCT	Exclusion criteria: history or current neurological disorders, alcohol abuse, epilepsy, mental retardation or any drug intake	CG (175) EG (172)	24 24	720 720	NR NR	Some activity Aerobic	Processing speed: Visual reaction time (reaction time), auditory reaction time (reaction time)
Sjöwall et al. (2019)	13–15 years	CT	Inclusion criteria: All students in seventh to ninth grades at both the active school and the control school	CG (59) EG (108)	36 36	100 100	NR NR	Some activity Aerobic	Working memory: Digit span (backward); Inhibition: Stroop (interference trial; seconds); Cognitive flexibility: Stroop (shifting trial; seconds)
Spitzera & Hollmann (2013)	12.8	CT	NR	CG (24)	16	NR	NR	Some activity	Attention: D2-test (number of correct answers); Mathematics and language: School grades
				EG (20)	16	90	NR	Aerobic	

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	Age, years (M± SD)	Study design	In- and exclusion criteria	Group (n)	Duration (weeks)	Dose (min/ week)	Intensity	Type of con- trol and intervention	Outcome measures and instruments; dependent variables
Spitzerb et al. (2013)	12.4	CT	NR	CG (33)	12	NR	NR	Some activity	Attention: D2-test (number of correct answers); Mathematics and language: School grades
Stroth et al. (2009)	19.65 ± 3.3	RCT	Exclusion criteria: history of neurological or psychiatric medical diseases, intake of medication affecting the nervous system	EG (55) CG (14)	12 6	90 NR	NR NR	Aerobic Some activity	Attention: D2-test (number of correct responses)
Stroth et al. (2010)	22.7 ± 5.7	CT	Exclusion criteria: history of head trauma, drug or alcohol abuse, history of neurological or psychiatric medical diseases, intake of medication affecting the nervous system	EG (14) CG (28)	6 16	90 NR	NR NR	Aerobic Some activity	Cognitive flexibility: dots mixed test (reaction time); Working memory: n-back test (reaction time); Inhibition: Stroop (reaction time)
Subramanian et al. (2015)	age range 12–17 years	RCT	Exclusion criteria: history or current neurological disorders, alcohol abuse, epilepsy, mental retardation or any drug intake	CG (175)	28	720	NR	Some activity	Attention: Letter cancellation test (time to complete the task); Cognitive flexibility: Trail making test (time to complete trial B)
Tarp et al. (2016)	12.88 ± 0.58	RCT	Inclusion criteria: following curriculum appropriate to their age	EG (172) CG (438)	28 20	720 NR	NR NR	Aerobic Some activity	Mathematics: school grades; Inhibition: Flanker task
Torbeyns et al. (2017)	14.3 ± 0.6	RCT	NR	EG (194) CG (23)	20 21	300 NR	NR NR	Aerobic Some activity	Mathematics and language: school grades
Venkunas et al. (2016)	17.28 ± 1.53	CT	Inclusion criteria: attend sailing sports school, with 3–4 years of training history	EG (21) CG (10) EG (8)	21 7 7	200 NR 210	NR NR NR	Aerobic Some activity Aerobic	Cognitive flexibility: Schulte-Corbov test (duration of the task and % errors); Working memory: free recall test (accuracy); Short term memory: forward digit span (mean number of digits)
Woost et al. (2018)	25.2 ± 3.55	CT	Inclusion criteria: normal weight, right-handed, normal or corrected-to-normal vision. No history of psychiatric, metabolic, neurological, respiratory, or cardiovascular diseases. Exclusion criteria: regular intake of medication or drugs, pregnancy, and breastfeeding, > 2.5 hours sports activities or > 1 hour video gaming.	CG (26) EG (26)	2 2	80 80	NR HR max: 170 bpm	Rest Aerobic	Processing speed: Digit Symbol test (correct answers)
Zheng et al. (2015)	20.6 ± 1.1	RCT	Exclusion criteria: engaged in a long term tai chi derived movements, member of the students' wushu-, taekwondo-, aerobic- or dance association, or suffered from severe cardiovascular disease or musculoskeletal disease.	CG (103) EG (95)	12 12	NR 300	NR NR	Some activity Aerobic	Attention: Schulte Grid test

n: number of participants; HRmean: mean heart rate during the intervention; bpm: beats per minute; NR: not reported; RCT: Randomized controlled trial; CT: controlled trial; EG: experimental group; CG: control group; GPA: Grade point average

Appendix C. Publication bias

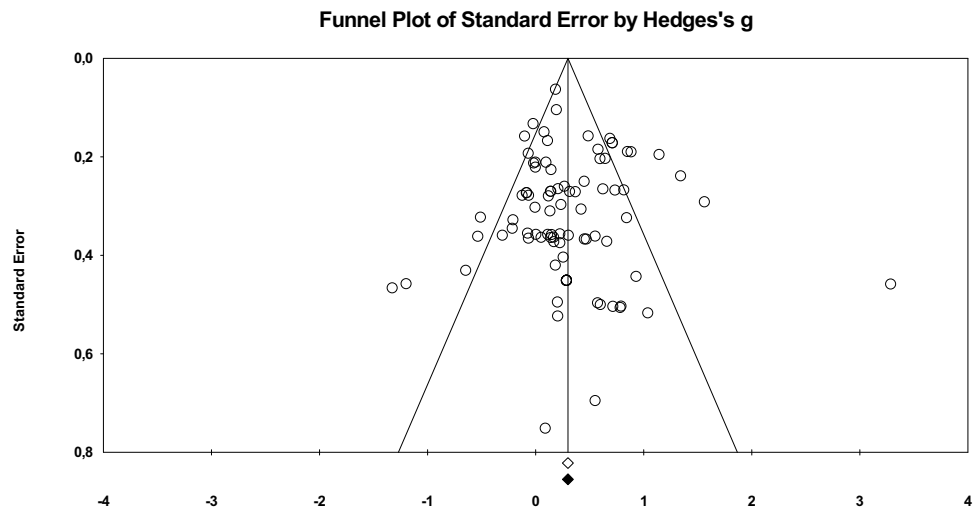


Figure C1. Funnel plot no publication bias acute interventions and neurocognitive functions.

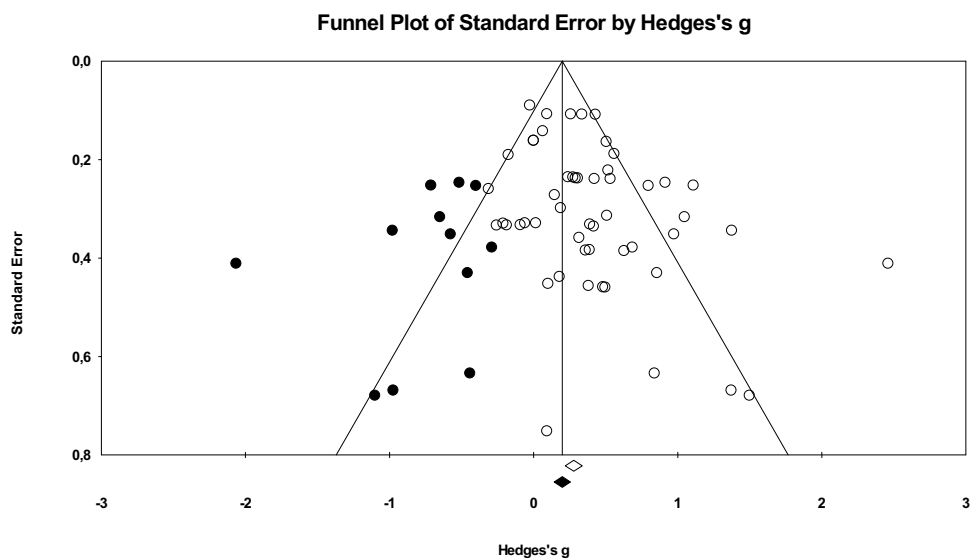


Figure C2. Funnel plot publication bias chronic interventions and neurocognitive functions.

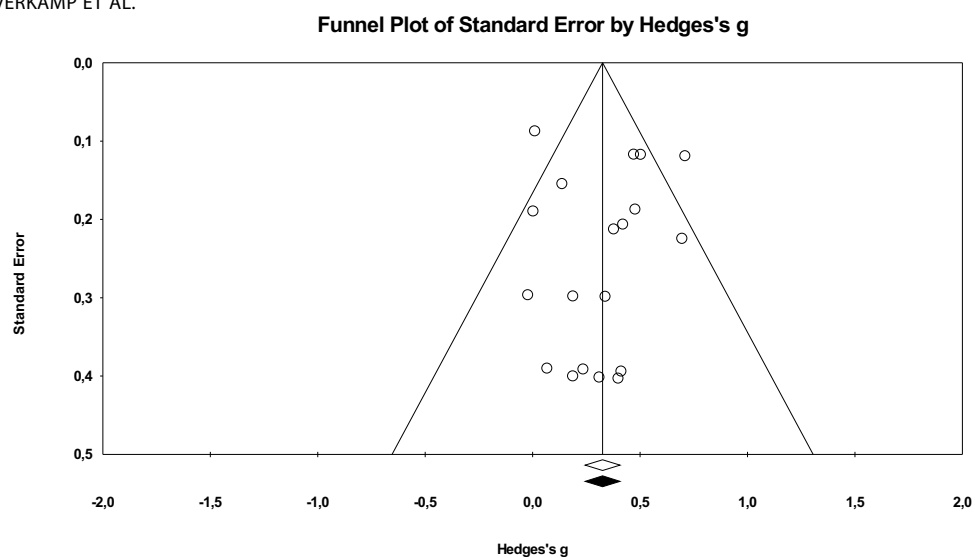


Figure C3. Funnel plot no publication bias chronic interventions and academic performance.