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

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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 (β=−0.02) and cognitive flexibility (β=−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 (β=0.02) and working memory (β=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.

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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; Verburgh 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

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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; Kashihara 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 x 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; Mezcua-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 (Ardoy 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.

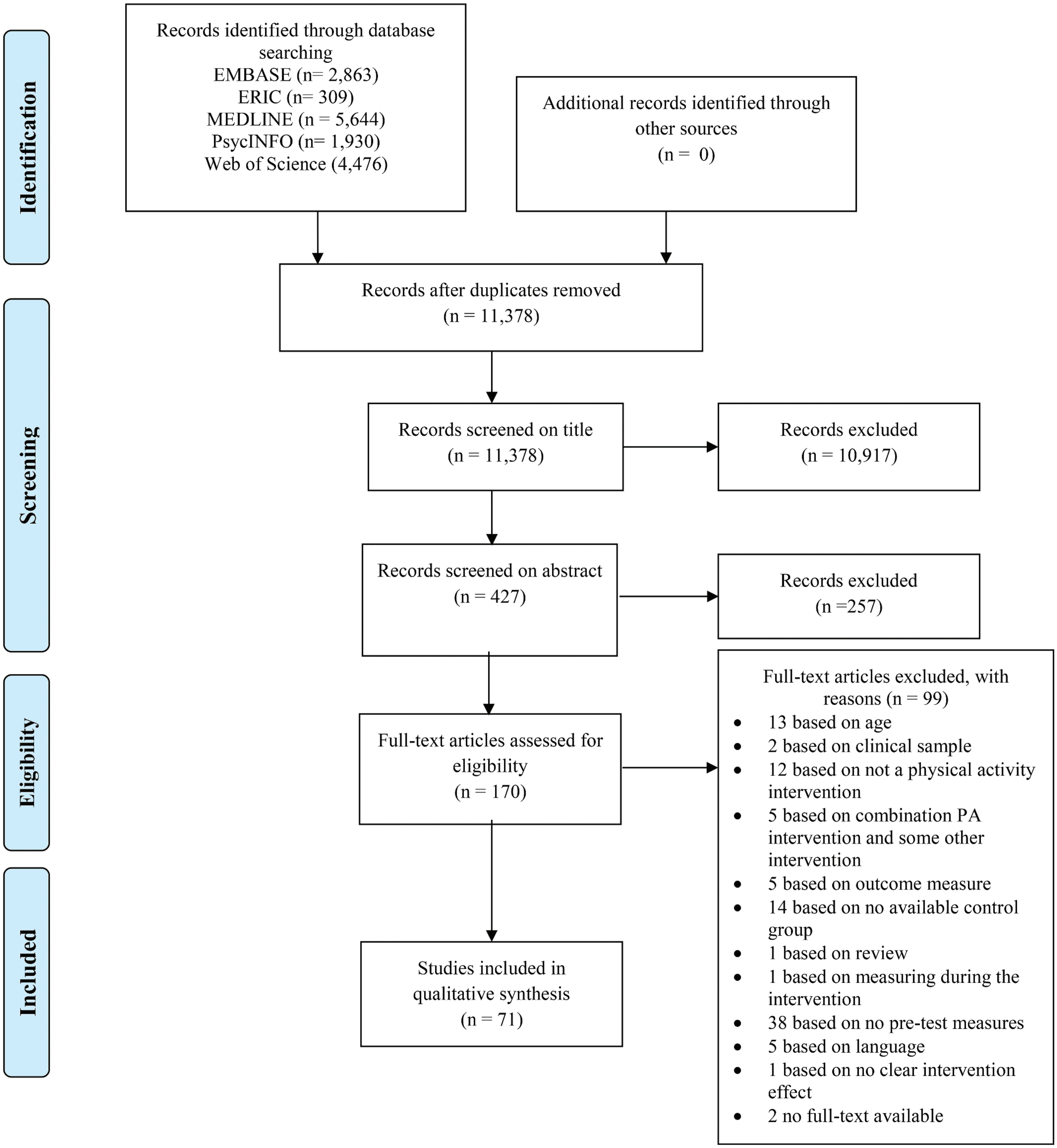

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) flow diagram of each stage of the study selection.

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

Fourty-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.

			Meta-analytic effect size			Heterogeneity		
Outcome	Sample size	*k*	Hedges' *g*	95%CI	*p* value	$I^{2\%}$	*Q*	*p* 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

Group by comparison	Study name	Subgroup	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z value	p-value
Overall cognitive outcomes			0.312	0.048	0.002	0.219	0.406	6.522	0.000
Processing speed	Du Rietz, 2019		-0.080	0.273	0.075	-0.616	0.455	-0.294	0.768
Processing speed	Guzman, 2017		0.206	0.524	0.274	-0.820	1.233	0.394	0.694
Processing speed	Moore, 2012		-0.072	0.355	0.126	-0.768	0.625	-0.201	0.840
Processing speed	Moore, 2012		-0.533	0.362	0.131	-1.242	0.176	-1.472	0.141
Processing speed	Murray, 2012		0.886	0.190	0.036	0.513	1.258	4.656	0.000
Processing speed	Murray, 2012		0.579	0.185	0.034	0.216	0.942	3.128	0.002
Processing speed	Murray, 2012		0.852	0.190	0.036	0.480	1.223	4.493	0.000
Processing speed	Prashant, 2020		0.645	0.204	0.041	0.246	1.044	3.169	0.002
Processing speed			0.394	0.164	0.027	0.072	0.716	2.396	0.017
Attention	Basso, 2015		-0.645	0.431	0.186	-1.490	0.200	-1.497	0.134
Attention	Budde, 2008		0.598	0.204	0.042	0.197	0.996	2.927	0.003
Attention	Chang, 2009	1	0.784	0.507	0.257	-0.209	1.776	1.547	0.122
Attention	Chang, 2009	2	1.040	0.517	0.266	0.026	2.054	2.010	0.044
Attention	Chang, 2009	3	0.792	0.504	0.254	-0.195	1.779	1.572	0.116
Attention	Hwang, 2016		0.268	0.260	0.088	-0.242	0.778	1.029	0.303
Attention	Hwang, 2018		-0.062	0.278	0.078	-0.606	0.483	-0.224	0.823
Attention	Hwang, 2018		-0.122	0.279	0.078	-0.668	0.424	-0.437	0.662
Attention	Lambourne, 2009		-0.509	0.323	0.104	-1.142	0.124	-1.575	0.115
Attention	Mezcua, 2019		0.669	0.163	0.027	0.370	1.009	4.227	0.000
Attention	Schwarck, 2019	1	0.288	0.451	0.204	-0.597	1.172	0.637	0.524
Attention	Schwarck, 2019	2	0.288	0.451	0.204	-0.597	1.172	0.637	0.524
Attention	Tine, 2012		0.489	0.158	0.025	0.179	0.798	3.054	0.002
Attention	Tine, 2014		1.343	0.239	0.057	0.842	1.812	5.620	0.000
Attention	Tsorbatzoudi, 1998	1	0.257	0.404	0.163	-0.535	1.049	0.636	0.525
Attention	Tsorbatzoudi, 1998	2	0.226	0.357	0.127	-0.437	0.925	0.633	0.527
Attention	van den Berg, 2018		0.186	0.063	0.004	0.063	0.310	2.949	0.003
Attention	Whyte, 2015		0.135	0.310	0.096	-0.473	0.743	0.435	0.664
Attention			0.340	0.105	0.011	0.134	0.545	3.238	0.001
Overall executive function			0.287	0.056	0.003	0.178	0.397	5.147	0.000
Cognitive flexibility	Aquirre-Loaiza a, 2019		0.370	0.271	0.074	-0.162	0.902	1.363	0.173
Cognitive flexibility	Aquirre-Loaiza b, 2019		0.053	0.364	0.132	-0.660	0.766	0.146	0.884
Cognitive flexibility	Basso, 2015		-1.325	0.467	0.218	-2.239	-0.410	-2.839	0.005
Cognitive flexibility	Benzing, 2016	1	0.471	0.389	0.135	-0.249	1.192	1.282	0.200
Cognitive flexibility	Benzing, 2016	2	-0.305	0.360	0.129	-1.011	0.400	-0.849	0.398
Cognitive flexibility	Coles, 2008		0.144	0.226	0.051	-0.299	0.588	0.637	0.524
Cognitive flexibility	Cooper, 2016		0.000	0.211	0.045	-0.414	0.414	0.000	1.000
Cognitive flexibility	Hwang, 2016		0.737	0.269	0.072	0.212	1.262	2.750	0.006
Cognitive flexibility	Jaffery, 2018		3.287	0.459	0.210	2.388	4.486	7.165	0.000
Cognitive flexibility	Schwarck, 2019	1	0.288	0.451	0.204	-0.597	1.172	0.637	0.524
Cognitive flexibility	Schwarck, 2019	2	0.288	0.451	0.204	-0.597	1.172	0.637	0.524
Cognitive flexibility	Murray, 2012		1.144	0.196	0.038	0.760	1.528	5.842	0.000
Cognitive flexibility	Tsai, 2014		0.143	0.271	0.073	-0.388	0.673	0.527	0.598
Cognitive flexibility	Tsai, 2016		0.140	0.271	0.073	-0.391	0.670	0.516	0.606
Cognitive flexibility	Wang, 2014		0.226	0.375	0.140	-0.509	0.960	0.603	0.547
Cognitive flexibility			0.372	0.190	0.036	-0.000	0.745	1.958	0.050
Working memory	Basso, 2015		0.932	0.443	0.197	0.063	1.801	2.101	0.036
Working memory	Basso, 2015		-1.196	0.450	0.210	-2.094	-0.290	-2.610	0.009
Working memory	Budde, 2010	1	0.170	0.373	0.139	-0.450	0.900	0.456	0.648
Working memory	Budde, 2010	2	-0.064	0.366	0.134	-0.780	0.653	-0.174	0.862
Working memory	Cooper, 2012		0.711	0.172	0.030	0.374	1.048	4.139	0.000
Working memory	Cooper, 2016		0.099	0.211	0.045	-0.316	0.513	0.466	0.641
Working memory	Hwang, 2018		0.092	0.752	0.565	-1.381	1.566	0.123	0.902
Working memory	Lambourne, 2012		-0.214	0.346	0.119	-0.892	0.463	-0.620	0.535
Working memory	Palmiere, 2018		0.113	0.167	0.028	-0.215	0.441	0.675	0.499
Working memory	Pontifex, 2009	1	0.453	0.367	0.135	-0.267	1.172	1.233	0.218
Working memory	Pontifex, 2009	2	0.169	0.363	0.132	-0.544	0.881	0.464	0.642
Working memory	van den Berg, 2018		-0.021	0.133	0.018	-0.282	0.240	-0.156	0.876
Working memory			0.140	0.125	0.016	-0.106	0.386	1.117	0.264
Inhibition	Akasuta, 2015		-0.003	0.303	0.092	-0.596	0.591	-0.008	0.993
Inhibition	Aquirre-Loaiza a, 2019		0.317	0.271	0.073	-0.214	0.848	1.171	0.242
Inhibition	Aquirre-Loaiza b, 2019		0.143	0.364	0.133	-0.570	0.857	0.394	0.694
Inhibition	Basso, 2015		0.184	0.420	0.177	-0.640	1.008	0.439	0.661
Inhibition	Benzing, 2016	1	0.661	0.372	0.138	-0.068	1.391	1.777	0.076
Inhibition	Benzing, 2016	2	0.305	0.360	0.129	-0.400	1.010	0.848	0.396
Inhibition	Browne, 2010		0.711	0.172	0.030	0.374	1.048	4.139	0.000
Inhibition	Chang, 2009	1	0.717	0.504	0.254	-0.271	1.705	1.422	0.155
Inhibition	Chang, 2009	2	0.601	0.501	0.251	-0.380	1.582	1.201	0.230
Inhibition	Chang, 2009	3	0.576	0.497	0.247	-0.398	1.550	1.159	0.247
Inhibition	Cooper, 2012		0.195	0.105	0.011	-0.010	0.401	1.861	0.063
Inhibition	Cooper, 2016		0.080	0.150	0.022	-0.214	0.373	0.533	0.594
Inhibition	Du Rietz, 2019		-0.084	0.273	0.075	-0.619	0.452	-0.306	0.760
Inhibition	Du Rietz, 2019		-0.066	0.193	0.037	-0.445	0.313	-0.342	0.732
Inhibition	Griffin, 2011		-0.207	0.328	0.108	-0.851	0.436	-0.632	0.527
Inhibition	Hwang, 2016		0.624	0.265	0.070	0.104	1.145	2.351	0.019
Inhibition	Lichtman, 1983		0.452	0.250	0.063	-0.038	0.942	1.807	0.071
Inhibition	Ludyga, 2019	1	0.554	0.362	0.131	-0.155	1.262	1.531	0.126
Inhibition	Ludyga, 2019	2	0.000	0.211	0.049	-0.434	0.434	0.000	1.000
Inhibition	Palmiere, 2018		-0.016	0.213	0.045	-0.433	0.401	-0.075	0.940
Inhibition	Peruyero, 2017	1	0.818	0.268	0.074	0.293	1.343	3.055	0.002
Inhibition	Peruyero, 2017	2	1.565	0.292	0.085	0.993	2.137	5.363	0.000
Inhibition	Schwarck, 2019	1	0.288	0.451	0.204	-0.597	1.172	0.637	0.524
Inhibition	Schwarck, 2019	2	0.288	0.451	0.204	-0.597	1.172	0.637	0.524
Inhibition	Sperlich, 2018		0.120	0.280	0.078	-0.428	0.669	0.430	0.667
Inhibition	Takahashi, 2019	1	0.198	0.378	0.143	-0.542	0.939	0.525	0.599
Inhibition	Takahashi, 2019	2	0.543	0.383	0.147	-0.209	1.294	1.416	0.157
Inhibition	Tsukamoto, 2017	1	0.204	0.495	0.245	-0.767	1.175	0.412	0.681
Inhibition	Tsukamoto, 2017	2	0.553	0.695	0.484	-0.810	1.916	0.795	0.426
Inhibition	Vonk, 2019		0.236	0.297	0.088	-0.346	0.818	0.794	0.427
Inhibition	Whyte, 2015		0.845	0.324	0.105	0.210	1.480	2.607	0.009
Inhibition	Zhou, 2019		0.467	0.236	0.056	0.003	0.930	1.974	0.048
Inhibition	Zimmer, 2016	1	0.114	0.358	0.128	-0.588	0.816	0.319	0.750
Inhibition	Zimmer, 2016	2	0.004	0.358	0.128	-0.697	0.706	0.012	0.990
Inhibition	Zimmer, 2016	3	0.149	0.358	0.128	-0.553	0.851	0.416	0.677
Inhibition			0.319	0.063	0.004	0.196	0.442	5.099	0.000

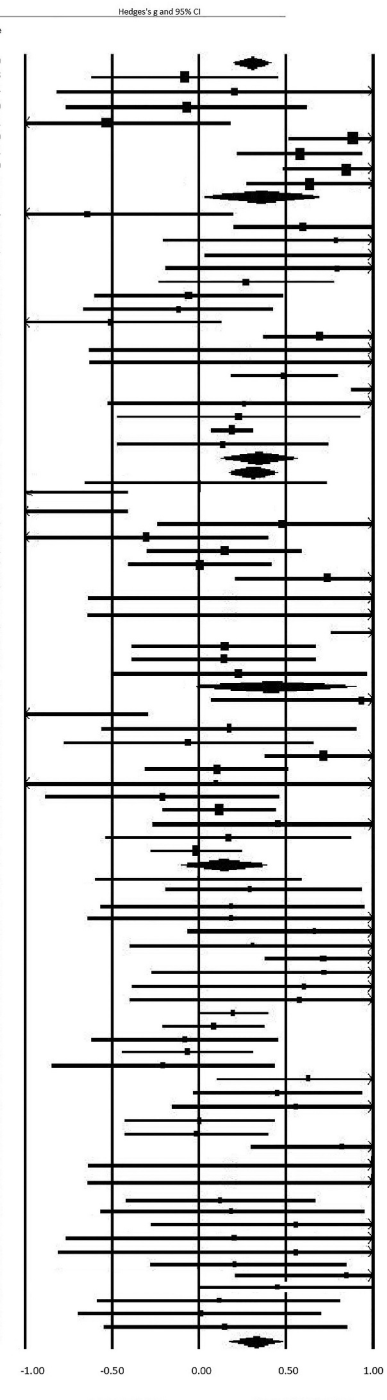

Figure 2. (a) Forest plot for meta-analysis regarding the effect of acute physical activity interventions on different cognitive outcomes. (b) Forest plot for meta-analysis regarding the effect of chronic physical activity interventions on different cognitive outcomes and academic performance.

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 (β = 0.02; 95% CI 0.00 to 0.03, p = 0.021) and working memory (β = 0.01; 95% CI 0.00 to 0.03, p = 0.033). Age, duration and

Group by comparison	Study name	Subgroup	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z value	p-value
Overall Cognitive outcome			0.261	0.039	0.002	0.184	0.338	6.628	0.000
Processing speed	Sharma et al., 2015		0.336	0.108	0.012	0.124	0.547	3.113	0.002
Processing speed	Sharma et al., 2015		0.258	0.108	0.012	0.047	0.469	2.401	0.016
Processing speed	Woost et al, 2018		0.079	0.273	0.075	-0.457	0.614	0.288	0.773
Processing speed			0.281	0.073	0.005	0.137	0.425	3.832	0.000
Attention	Duarte, 2020		1.048	0.316	0.100	0.427	1.668	3.310	0.001
Attention	Lenneman, 2013		1.376	0.344	0.118	0.702	2.050	4.000	0.000
Attention	Lenneman, 2013		0.509	0.314	0.098	-0.106	1.124	1.623	0.105
Attention	Pinto-Escalona, 2019		0.560	0.188	0.035	0.191	0.929	2.974	0.003
Attention	Purohit, 2017		0.914	0.247	0.061	0.430	1.397	3.705	0.000
Attention	Spitzer[a], 2013		0.188	0.298	0.089	-0.396	0.772	0.632	0.528
Attention	Spitzer[b], 2013		0.517	0.222	0.049	0.083	0.952	2.334	0.020
Attention	Stroth, 2009		0.686	0.378	0.143	-0.055	1.428	1.815	0.070
Attention	Subramanian, 2015		0.430	0.108	0.012	0.217	0.642	3.963	0.000
Attention	Torbyens, 2017		-0.312	0.259	0.067	-0.820	0.196	-1.204	0.229
Attention	Zheng, 2014		0.064	0.142	0.020	-0.214	0.342	0.452	0.652
Attention			0.499	0.122	0.015	0.260	0.738	4.088	0.000
Overall executive function			0.332	0.074	0.005	0.188	0.477	4.503	0.000
Cognitive flexibility	Costigan, 2016	1	0.389	0.383	0.147	-0.362	1.140	1.014	0.310
Cognitive flexibility	Costigan, 2016	2	0.628	0.385	0.149	-0.128	1.383	1.629	0.103
Cognitive flexibility	Johann, 2016	1	0.092	0.752	0.565	-1.381	1.566	0.123	0.902
Cognitive flexibility	Johann, 2016	2	0.180	0.438	0.192	-0.679	1.038	0.410	0.682
Cognitive flexibility	Matthews, 2016		0.856	0.430	0.185	0.013	1.698	1.990	0.047
Cognitive flexibility	Purohit, 2017		0.274	0.236	0.056	-0.188	0.736	1.162	0.245
Cognitive flexibility	Stroth, 2010		0.422	0.239	0.057	-0.046	0.890	1.767	0.077
Cognitive flexibility	Subramanian, 2015		0.093	0.107	0.011	-0.117	0.303	0.869	0.385
Cognitive flexibility	Venckunas, 2016		0.482	0.489	0.211	-0.418	1.381	1.050	0.294
Cognitive flexibility	Venckunas, 2016		0.381	0.456	0.208	-0.513	1.276	0.836	0.403
Cognitive flexibility			0.235	0.080	0.006	0.079	0.391	2.956	0.003
Working memory	Jeon, 2017	1	0.839	0.634	0.402	-0.404	2.081	1.323	0.186
Working memory	Jeon, 2017	2	1.498	0.679	0.461	0.167	2.829	2.206	0.027
Working memory	Jeon, 2017	3	1.372	0.669	0.447	0.061	2.683	2.051	0.040
Working memory	Johann, 2016	1	-0.091	0.333	0.111	-0.743	0.561	-0.274	0.784
Working memory	Johann, 2016	1	0.417	0.335	0.112	-0.240	1.075	1.244	0.214
Working memory	Johann, 2016	2	-0.061	0.329	0.108	-0.706	0.584	-0.185	0.853
Working memory	Johann, 2016	2	0.391	0.331	0.110	-0.259	1.040	1.179	0.238
Working memory	Lennemann, 2013		2.461	0.411	0.169	1.655	3.267	5.985	0.000
Working memory	Ludyga, 2018		0.360	0.384	0.148	-0.393	1.113	0.937	0.349
Working memory	Purohit, 2017		0.139	0.235	0.055	-0.223	0.700	1.014	0.310
Working memory	Purohit, 2017		1.109	0.252	0.064	0.615	1.604	4.399	0.000
Working memory	Sjöwall, 2019		0.505	0.164	0.027	0.184	0.825	3.086	0.002
Working memory	Stroth, 2010		0.290	0.237	0.056	-0.175	0.756	1.222	0.222
Working memory	Venckunas, 2016		0.101	0.452	0.204	-0.785	0.987	0.223	0.824
Working memory			0.587	0.160	0.025	0.274	0.900	3.677	0.000
Inhibition	Johann, 2016		-0.257	0.334	0.111	-0.911	0.397	-0.771	0.441
Inhibition	Johann, 2016		-0.211	0.330	0.109	-0.858	0.435	0.642	0.521
Inhibition	Ludyga, 2018		0.316	0.359	0.129	-0.387	1.019	0.881	0.378
Inhibition	Ludyga, 2019		0.974	0.351	0.123	0.285	1.662	2.771	0.006
Inhibition	Purohit, 2017		0.533	0.239	0.057	0.065	1.001	2.232	0.026
Inhibition	Sjöwall, 2019		0.000	0.161	0.026	-0.316	0.316	0.000	1.000
Inhibition	Stroth, 2010		0.306	0.238	0.056	-0.160	0.772	1.288	0.198
Inhibition	Tarp, 2016		-0.026	0.090	0.008	-0.201	0.149	-0.291	0.771
Inhibition	Torbeyns, 2017		0.146	0.272	0.074	-0.387	0.678	0.537	0.591
Inhibition			0.155	0.105	0.011	-0.050	0.361	1.480	0.139
Academic performance			0.338	0.077	0.006	0.187	0.489	4.387	0.000
Grade point average	Ardoy, 2014		0.067	0.390	0.152	-0.697	0.832	0.173	0.863
Grade point average	Ardoy, 2014		0.399	0.403	0.162	-0.391	1.189	0.990	0.322
Grade point average	Butzer, 2015		0.420	0.206	0.043	0.016	0.825	2.037	0.042
Grade point average	Hagins, 2016		0.003	0.190	0.036	-0.369	1.189	0.990	0.322
Grade point average			0.201	0.125	0.016	-0.044	0.446	1.605	0.108
Language	Ardoy, 2014		0.412	0.394	0.155	-0.360	1.184	1.046	0.295
Language	Ardoy, 2014		0.310	0.402	0.131	-0.476	1.097	0.773	0.439
Language	Pinto-Escalona, 2019		0.477	0.187	0.035	0.110	0.844	2.549	0.011
Language	Spitzer[a], 2013		0.378	0.213	0.045	-0.039	0.795	1.778	0.075
Language	Spitzer[b], 2013		0.138	0.155	0.024	-0.165	0.441	0.890	0.373
Language	Torbeyns, 2017		0.339	0.299	0.089	-0.247	0.924	1.134	0.257
Language			0.310	0.093	0.009	0.129	0.492	3.348	0.001
Mathematics	Ardoy, 2014		0.236	0.391	0.153	-0.532	1.003	0.602	0.547
Mathematics	Ardoy, 2014		0.188	0.400	0.160	-0.596	0.972	0.469	0.639
Mathematics	Kauts, 2009		0.710	0.119	0.014	0.477	0.943	5.964	0.000
Mathematics	Spitzer[a], 2013		0.188	0.298	0.089	-0.396	0.772	0.632	0.528
Mathematics	Spitzer[b], 2013		0.696	0.224	0.050	0.256	1.136	3.100	0.002
Mathematics	Tarp, 2016		0.011	0.087	0.008	-0.160	0.181	0.121	0.904
Mathematics	Torbeyns, 2017		-0.021	0.296	0.088	-0.602	0.559	-0.073	0.942
Mathematics			0.310	0.165	0.027	-0.014	0.633	1.875	0.061

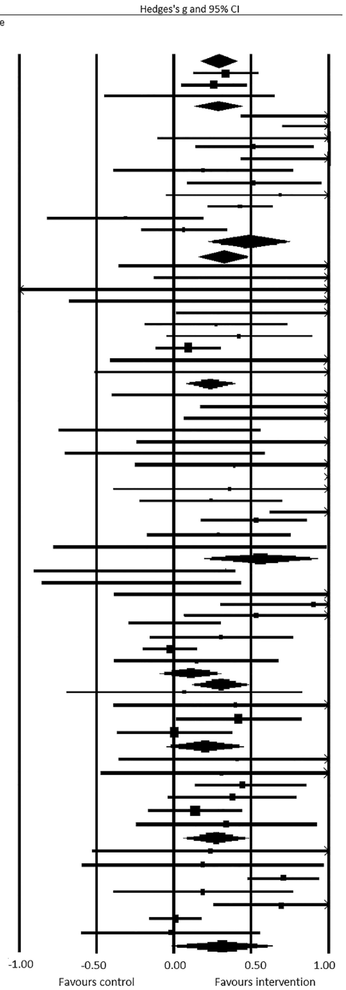

Figure 2. (Continued).

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 × 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 s *d*	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 × 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 s *d*	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 × 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.

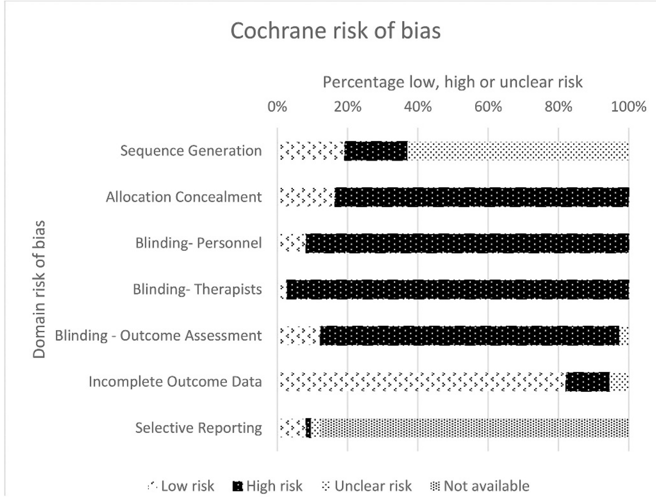

Figure 3. Analysis of the risk of bias in included studies in accordance with the cochrane collaboration guidelines.

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, Cavero-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 × 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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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 comprehen*[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)
				EG (10)	15	50% oxygen intake	Aerobic	
Aquirre-Loaiza et al. (2019)	20.7 ± 2.5	RCT	Exclusion criteria: score >30 on the Beck Depression Inventory, cardiovascular problems	CG (30)	45	NR	Rest	Inhibition: Stroop (seconds); Cognitive flexibility: Trail making test (seconds)
				EG (30)	45	HRmean 137 bpm	Aerobic	
Aquirre-Loaiza et al. (2019)	21.6 ± 1.8	RCT	Exclusion criteria: score >30 on the Beck Depression Inventory, cardiovascular problems	CG (27)	30	NR	Rest	Inhibition: Stroop (seconds); Cognitive flexibility: Trail making test (seconds)
				EG (26)	30	HRmean 143 bpm	Aerobic	
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.	CG (42)	60	NR	Rest	Inhibition: Stroop task (interference score); Working Memory: Symbol Digit 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)
				EG (43)	60	HRmean 161 bpm	Aerobic	
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	CG (21)	15	HRmean 82 bpm	Rest	Inhibition: D-KEF (number of created objects); Cognitive flexibility: D-KEF (number of created objects)
engagement				EG1 (21)	15	HRmean 141 bpm	Cognitive	
			EG2 (23)		15	HRmean 152 bpm	Aerobic	
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)	30	HRmean 81 bpm	Rest	Inhibition: Stroop task (reaction time)
				EG (20)	30	HRmean 165 bpm	Aerobic	
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
				EG (47)	10	HRmean 122 bpm	Cognitive	engagement
Budde et al. (2010)	14.4 ± 0.5	RCT	Exclusion criteria: dyslexia, BMI >25, mental or physical impairments or psychoactive substances	CG (21)	12	HRmean 86 bpm	Rest	Working Memory: Letter Digit Span (number of correct answers)
				EG1 (18)	12	HRmean 124 bpm	Aerobic	
				EG2 (20)	12	HRmean 160 bpm	Aerobic	
Chang and Etnier (2009)	26.0 ± 3.2	RCT	Inclusion criteria: meet the criteria of PAR-Q	CG (16)	30	HRmean 79 bpm	Rest	Inhibition: Stroop (seconds); Attention: Paced Auditory serial addition task (correct answers in trial 4)
				EG1 (16)	30	HRmean 95 bpm	Resistance	
				EG2 (16)	30	HRmean 116 bpm	Resistance	
				EG3 (17)	30	HRmean 136	Resistance	
Chang et al. (2011)	22.3 ± 2.0	RCT	Inclusion criteria: meet the criteria of PAR-Q	CG (22)	30	HRmean 75 bpm	Rest	Planning: Tower of London (execution time, seconds)
				EG (20)	30	HRmean 154 bpm	Aerobic	
Coles et al. (2008)	22.2 ± 1.6	cross over	Exclusion criteria: contradiction for maximal exercise	CG (18)	40	NR	Rest	Cognitive flexibility: Visual shift task of Kramer (response time)

(*Continued*)

(Continued).

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)	40	HRmean 141 bpm	Aerobic	Working Memory: Sternberg paradigm (reaction time); Inhibition: Stroop (seconds)
				CG (45)	10	NR	Rest	
				EG (45)	10	HRmean 172 bpm	Aerobic	
Cooper et al. (2016)	12.6 ± 0.6	cross over	Inclusion criteria: good health following the health screen questionnaire	CG (44)	10	HRmean 90 bpm	Rest	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)
				EG (44)	10	HRmean 181 bpm	Aerobic	
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
				EG (26)	30	HR end session 180 bpm	Aerobic	
Griffin et al. (2011)	22.0 ± 2.0	CT	Inclusion criteria: be able to participate in PE class	CG (13)	30	NR	Rest	Inhibition: Stroop
				EG (29)	NR	NR	Aerobic	
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	CG (30)	30	NR	Rest	Attention Vienna Test system
				EG (62)	30	60–70% Hrmax	Aerobic	
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
				EG (29)	20	HRmean 158 bpm	Aerobic	
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	CG (25)	30	NR	Rest	Working Memory: Delayed match memory task; Attention: psychomotor vigilence test
				EG (25)	30	HRmean 125 bpm	Aerobic	
Jaffery et al. (2018)	21.4 ± 0.5	RCT	Exclusion criteria: smoking, caffeine or exercise 6 hours before measurements.	CG (22)	10	NR	Rest	Cognitive flexibility: Trail making test (score on B-trial)
				EG (22)	5	HRmean 116 bpm	Aerobic	
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
				EG (19)	40	HRmean 143 bpm	Aerobic	
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	CG (16)	25	NR	Rest	Working Memory: Operation Span Task
				EG (16)	35	90% ventilary threshold	Aerobic	
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
				EG1 (34)	20	HRmean 143 bpm	Aerobic	
				EG2 (32)	20	HRmean 154 bpm	Aerobic	
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	CG (81)	20	HRmean 91 bpm	Some activity	Memory: ad hoc test; Attention: D2-test
				EG (77)	20	HRmean 157 bpm	Aerobic	
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 (15)	60	NR	Rest	Processing speed: Visual discrimination performance
				EG (15)	60	90% ventilary threshold	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)
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)
				EG (60)	30	75% HRmax	Aerobic	
Palmiere 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	CG (35)	30	NR	Rest	Inhibition: Flanker task; Working Memory: N-back test, Memory: Memory recognition task
				EG (35)	30	NR	Resistance	
Peruyero et al. (2017)	16.39 ± 0.68	cross over	NR	CG (44)	20	NR	Rest	Inhibtion: Stroop
				EG1 (44)	30	light	Aerobic	
				EG2 (44)	30	moderate	Aerobic	
Pontifex et al. (2009)	20.2 ± 0.3	cross over	Inclusion criteria: normal or corrected to normal vision and no neurological diseases	CG (21)	30	HRmean 68 bpm	Rest	Working Memory: Sternberg task
				EG1 (21)	30	HRmean 162 bpm	Aerobic	
				EG2 (21)	30	HRmean 123 bpm	Resistance	
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.	CG (50)	10	NR	Rest	Processing speed: Reaction time (visual and auditory)
				EG (50)	5	NR	Aerobic	
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.	CG (13)	35	NR	Rest	Inhibition: Stroop (seconds); Attention: D2-test; Cognitive flexibility: Trailmaking test
				EG1 (13)	35	NR	Aerobic	
				EG2 (13)	35	NR	Aerobic	
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
				EG (60)	17	NR	Aerobic	
				EG (60)	85	NR	Aerobic	
Sperlich et al. (2018)	22 ± 2	cross over	Exclusion criteria: routine experience with HIIT	CG (12)	6	HRmean 75 bpm	Rest	Inhibition: Stroop
				EG (12)	6	HRmean 166 bpm	Aerobic	
Takahashi et al. (2019)	20.9 ± 0.89	Cross over	Inclusion criteria: free of any cardiopulmonary and metabolic diseae and visual disorder. No alcohol use or strenuous physical activity 24 hours before experiment, no smoking, foor or caffeine consumption 2 hours before experiment	CG (20)	10	HR peak: 74 bpm	Rest	Inhibition: Stroop
				EG1 (20)	10	HR peak: 160 bpm	Aerobic	
				EG2 (20)	10	HR peak: 159 bpm	Cognitive	engagement
Tine (2014)	17–21	RCT	Exclusion criteria: learning dissabilities	CG (39)	12	NR	Rest	Language: reading comprehension task
				EG (46)	12	70–80% Hrmax	Aerobic	
Tine and Butler (2012)	12.3	RCT	Exclusion criteria: reduced priced lunch	CG (78)	12	NR	Rest	Attention: D2-test
				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)	47	NR	Rest	Cognitive flexibility: task-switching test
				EG1 (20)	30	>75% ventilary threshold	Aerobic	
				EG2 (20)	30	<45% ventilatory threshold	Aerobic	
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)	47	NR	Rest	Inhibition: visuospatial attention paradigm
				EG1 (20)	30	>75% ventilary threshold	Aerobic	
				EG2 (20)	30	<45% ventilatory threshold	Aerobic	
Tsorbatzoudis et al. (1998)	20.0 ± 3.2	CT	NR	CG (11)	10 vs 35	NR	Rest	Attention: Vienna Test system
				EG1 (12)	5	HRmean178 bpm	Aerobic	
				EG2 (24)	35	HRmean 167 bpm	Aerobic	
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	CG (12)	17	HRmean 66 bpm	Rest	Inhibition: Stroop
				EG1 (12)	17	HRmean 105 bpm	Resistance	
				EG2 (12)	17	HRmean 142 bpm	Resistance	
van den Berg et al. (2018)	12.3 ± 0.6	cross over	Exclusion criteria: a medical condition that could affect concentration or memory	CG (99)	20	NR	Rest	Working Memory: N-back test; Attention: ANT
				EG (99)	20	HRmean 135 bpm	Aerobic	
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.	CG (22)	30	HRmean 92 bpm	Rest	Inhibition: Stroop
				EG (22)	30	HRmean 120 bpm	Resistance	
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
				EG (14)	30	HRmean 151 bpm	Aerobic	
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	CG (20)	10	NR	NR	Inhibition: Stroop; Working Memory: Symbol Digit Modality test
				EG (20)	10	HRmax 188 bpm	Aerobic	
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)	25	Rest	Rest	Inhibition: Stroop (ms incongruent trials)
				EG (36)	25	HRmean 133 bpm	Aerobic	
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)	35	NR	Some activity	Inhibition: Stroop
				EG1 (30)	35	45–50% HRmax	Aerobic	
				EG2 (30)	35	65–70% HRmax	Aerobic	
				EG3 (30)	35	85–90% HRmax	Aerobic	

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

	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
Ardoy 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	CG (17)	17	110	HRmean 116 bpm	Some activity	GPA, mathematics, language: school grades
				EG1 (20)	17	220	HRmean 129 bpm	Aerobic	
				EG2 (17)	17	220	HRmean 147 bpm	Aerobic	
Butzer et al. (2015)	NR	RCT	Inclusion criteria: 9th or 10th grade in a public high school	CG (51)	12	85	NR	Some activity	GPA: school grades
				EG (44)	12	85	NR	Yoga	
Costigan et al. (2016)	15.8 ± 0.6	RCT	NR	CG (22)	8	NR	NR	Some activity	Working Memory: Trail making test (time to complete trial B)
				EG1 (21)	8	30	HRmean 148 bpm	Aerobic	
				EG2 (22)	8	30	HRmean 155 bpm	Resistance and Aerobic	
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.	CG (22)	4	10	NR	Rest	Attention: D2 test
				EG (22)	4	10	NR	Yoga	
Hagins & Rundle (2016)	15.3 ± 1.0	RCT	Inclusion criteria: All students who were cleared for PE class	CG (64)	40	90	NR	Some activity	GPA: School grades
				EG (48)	40	90	NR	Yoga	
Heisz et al. (2017)	20.71 ± 2.73	RCT	Exclusion criteria: more than 1 hour of vigorous exercise a week	CG (32)	6	60	NR	Some activity	Memory: mnemonic similarity task (accuracy)
				EG (34)	6	60	NR	Aerobic	
Jeon & Ha (2017)	15.18 ± 0.61	RCT	Exclusion criteria: history of physical illness or participating in any sport activities outside PE	CG (10)	12	120	light	Some activity	Working memory: Digit span (total score forward and backward)
				EG1 (10)	12	172	HRmean 121 bpm	Aerobic	
				EG2 (10)	12	132	HRmean 142 bpm	Aerobic	
				EG3 (10)	12	104	HRmean 162 bpm	Aerobic	
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	CG (24)	6	NR	NR	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)
				EG1 (32)	6	90	NR	Cognitive engagement	
				EG2 (35)	6	90	50–70 max pulse rate	Aerobic	
Kauts & Sharma (2009)	age range 14–15 years	RCT	NR	CG (137)	7	NR	NR	Some activity	Mathematics, Social studies and Science: Standardized tests
				EG (164)	7	300	NR	Yoga	
Lenneman 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	CG (18)	6	NR	NR	Some activity	Working memory: n-back task (reaction time and accuracy); Attention: visual vigilance task (percentage correct answers), dichotic listening task (percentage correct answers)
				EG (23)	6	NR	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
LudygaGerber, Kamijo (2018)	12.45 ± 0.7	RCT	Inclusion criteria: right handed, normal or corrected-to-normal vision. Exclusion criteria: attending special education	CG (16)	8	100	NR	Sedentary	Working memory: Sternberg (reaction time and accuracy)
			services related to cognitive impairments or attentional disorders, or receiving pharmacotherapy for mental disorders, colorblindness, or medical condition which increase health risks during exercise	EG (17)	8	100	HRmean 135 bpm	Aerobic and congitive engaging	
Ludgya et al. (2018)	12.45 ± 0.7	RCT	See in- and exclusion criteria Ludgya, Gerber, Kamijo et al. (2018)	CG (16)	8	100	NR	Sedentary	Inhibition: Stroop (reaction time and accuracy)
				EG (17)	8	100	HRmean 135 bpm	Combination aerobic and cognitively	
challenging Ludgya, 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 pharmaco-logical treatment for any mental disorder.	CG (16)	8	100	NR	Rest	Inhibition: Stroop challenging
				EG (19)	8	100	HRmean 135 bpm	Combination aerobic and cognitively	
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)	4	NR	NR	Some activity	Cognitive flexibility: Wisconsin Card Sorting Test (perspective errors)
				EG (11)	4	180	NR	Coordination	
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)
				EG (56)	1	50	NR	EG: Aerobic	
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	CG (32)	12	NR	NR	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 Trial A); Cognitive flexibility: Trail making test (time to complete Trail B)
				EG (40)	12	360	NR	yoga	
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)	24	720	NR	Some activity	Processing speed: Visual reaction time (reaction time), auditory reaction time (reaction time)
				EG (172)	24	720	NR	Aerobic	
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)	36	100	NR	Some activity	Working memory: Digit span (backward); Inhibition: Stroop (interference trial; secondes); Cognitive flexibility: Stroop (shifting trial; seconds)
				EG (108)	36	100	NR	Aerobic	
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 control 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
				EG (55)	12	90	NR	Aerobic	
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	CG (14)	6	NR	NR	Some activity	Attention: D2-test (number of correct responses)
				EG (14)	6	90	NR	Aerobic	
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	CG (28)	16	NR	NR	Some activity	Cognitive flexibility: dots mixed test (reaction time); Working memory: n-back test (reaction time); Inhibition: Stroop (reaction time)
				EG (47)	16	NR	NR	Aerobic	
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 cancelation test (time to complete the task); Cognitive flexibility: Trail making test (time to complete trial B)
				EG (172)	28	720	NR	Aerobic	
Tarp et al. (2016)	12.88 ± 0.58	RCT	Inclusion criteria: following curriculum appropriate to their age	CG (438)	20	NR	NR	Some activity	Mathematics: school grades; Inhibition: Flanker task
				EG (194)	20	300	NR	Aerobic	
Torbeyns et al. (2017)	14.3 ± 0.6	RCT	NR	CG (23)	21	NR	NR	Some activity	Mathematics and language: school grades
				EG (21)	21	200	NR	Aerobic	
Venckunas et al. (2016)	17.28 ± 1.53	CT	Inclusion criteria: attend sailing sports school, with 3–4 years of training history	CG (10)	7	NR	NR	Some activity	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)
				EG (8)	7	210	NR	Aerobic	
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)	2	80	NR	Rest	Processing speed: Digit Symbol test (correct answers)
				EG (26)	2	80	HR max: 170 bpm	Aerobic	
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)	12	NR	NR	Some activity	Attention: Schulte Grid test
				EG (95)	12	300	NR	Aerobic	

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

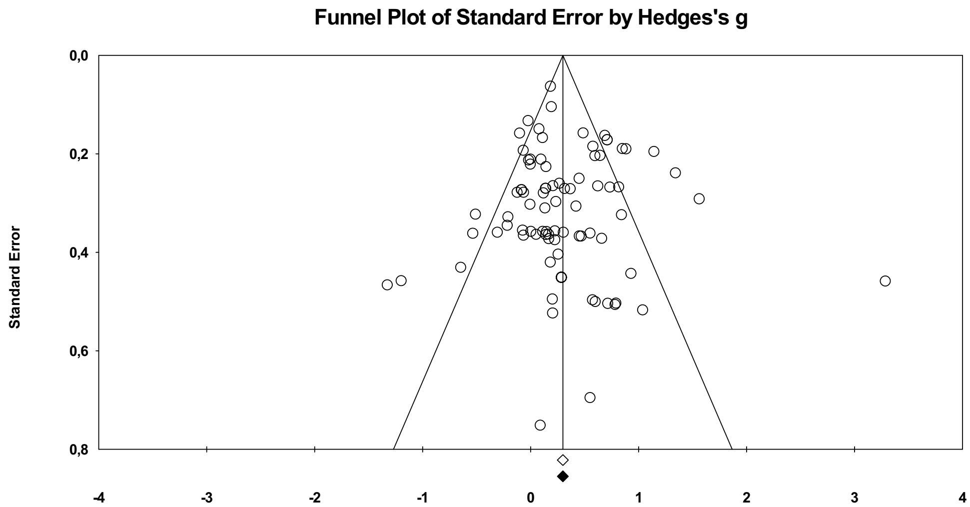

Figure C1. Funnel plot no publication bias acute interventions and neurocognitive functions.

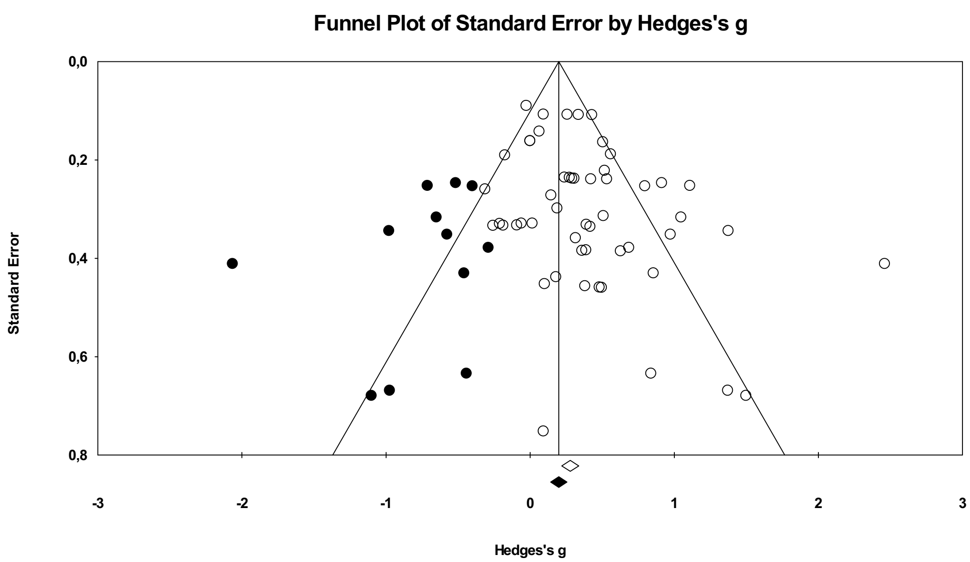

Figure C2. Funnel plot publication bias chronic interventions and neurocognitive functions.

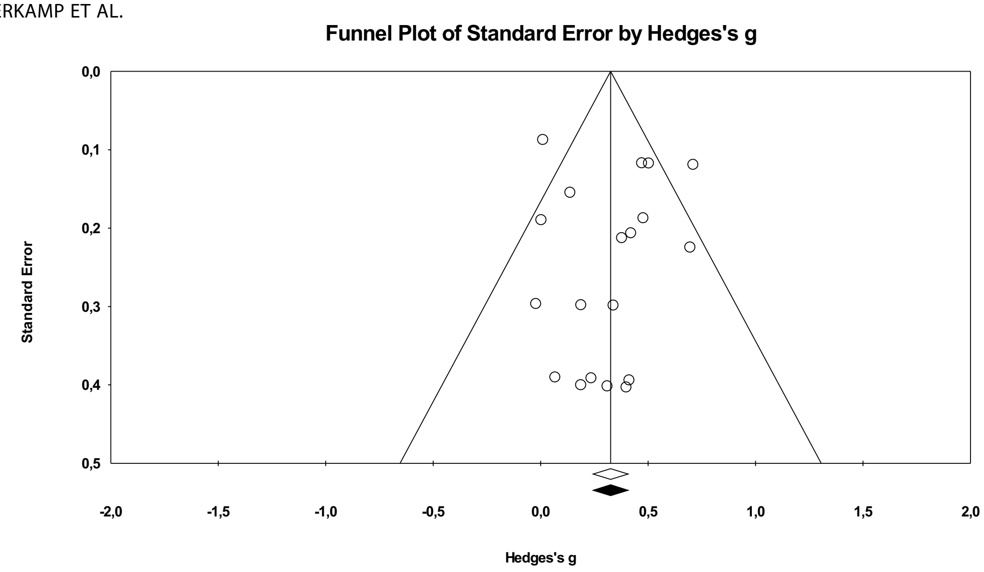

Figure C3. Funnel plot no publication bias chronic interventions and academic performance.