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Review

Effects of physical activity on executive functions, attention and academic performance in preadolescent children: a meta-analysis

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ABSTRACT

Objectives: The aim of this meta-analysis was to provide a systematic review of intervention studies that investigated the effects of physical activity on multiple domains of executive functions, attention and academic performance in preadolescent children (6–12 years of age). In addition, a systematic quantification of the effects of physical activity on these domains is provided.
Design: Systematic review and meta-analysis.
Methods: Searches of electronic databases and examining relevant reviews between 2000 and April 2017 resulted in 31 intervention studies meeting the inclusion criteria. Four subdomains of executive functions (inhibition, working memory, cognitive flexibility and planning), three subdomains of attention (selective, divided and sustained) and three subdomains of academic performance (mathematics, spelling and reading) were distinguished. Effects for different study designs (acute physical activity or longitudinal physical activity programs), type of physical activity (aerobic or cognitively engaging) and duration of intervention were examined separately.
Results: Acute physical activity has a positive effect on attention (g = 0.43; 95% CI = 0.09, 0.77; 6 studies), while longitudinal physical activity programs has a positive effect on executive functions (g = 0.24; 95% CI = 0.09, 0.39; 12 studies), attention (g = 0.90; 95% CI = 0.56, 1.24; 1 study) and academic performance (g = 0.26; 95% CI = 0.02, 0.49; 3 studies). The effects did depend on the subdomain.
Conclusions: Positive effects were found for physical activity on executive functions, attention and academic performance in preadolescent children. Largest effects are expected for interventions that aim for continuous regular physical activity over several weeks.

1. Introduction

European preadolescent children (aged 6–12 years) spend 209 min/day (64%) of their school time in sedentary activities, while spending only 16 min/day (5%) in moderate to vigorous physical activity (MVPA).[1] This is concerning because apart from the clear physical health benefits of MVPA in children,[2,3] an expanding body of literature shows that MVPA is positively associated with key cognitive functions that are important for success in school.[4] Recently, many researchers have been focusing on the executive functions hypothesis.[5] This hypothesis states that MVPA leads to increased activity in selective parts of the brain structural network and especially improves executive functions.[5] Executive functions are higher order cognitive functions that are responsible for initiating, adapting, regulating, monitoring, and controlling information processes and behavior.[6,7] These functions are often thought of as an important prerequisite for successful learning in preadolescent children.[7] Other researchers have focused on more lower-order cognitive tasks, with particular interest in attention.[8] Attention is defined as a cognitive state in which a child focuses on a selection of available perceptual information.[9] Although attention is closely related to executive functions,[10] it can be seen as a lower order cognitive function and it is mostly measured with performance on reaction time or other simple decisional tasks.[11] Improvements in these cognitive functions as a result of increased physical activity may, in turn, improve children's academic performance.

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Within the preadolescent age range, previous meta-analyses have shown that enhanced cognitive functioning as a result of physical activity is most clearly seen in executive functions[12] and attention.[8] These cognitive functions are indispensable for success throughout life and are often thought of as an important prerequisite for successful learning.[7] Several underlying mechanisms might explain the effects of physical activity on cognitive functions. First, a single bout of physical activity (acute physical activity) is thought to immediately elevate the child's level of physiological arousal, which in turn facilitates the cognitive performance by an increased allocation of attention.[13,14] From a psycho-physiological perspective, acute physical activity triggers an increase of neurotransmitters (e.g. epinephrine, dopamine, brain-derived neurotrophic factors), which are thought to enhance cognitive processes.[15,16] Secondly, according to the cardiovascular fitness hypothesis, an intervention program that contains continuous aerobic physical activity over several weeks (longitudinal physical activity program) is thought to improve aerobic fitness and consequently improve cognitive performance.[17] This hypothesis is supported by the argue that physical activity enhances the angiogenesis[18] and neurogenesis[16] in areas of the brain that support memory and learning, subsequently enhancing cognitive performance.[19] More recently, other researchers argue that instead of 'simple' aerobic physical activity (i.e. physical activity that is intended to improve cardiovascular performance), cognitively engaging physical activity (i.e. physical activity that is cognitively challenging) is more beneficial for cognition.[20–22] Cognitive engagement is the amount of both the allocation of attention and the cognitive effort that are needed for a certain activity.[20,23] Physical activities with a relatively high cognitive engagement (e.g. tennis, where children have to plan strategically, focus attention, and so forth) are suggested to have more effect on executive functions, compared to physical activities with a relatively low cognitive engagement (e.g. long distance running, which involves more automated movements).[20,22] These different underlying mechanisms suggest that the effects for physical activity to improve attention, executive functions and academic performance in children might depend on the duration or type (aerobic vs cognitively engaging) of physical activity is chosen.

Previously, studies have mainly focused on the association between physical activity and overall cognitive functioning in children. The results from a previous meta-analysis showed a positive association between physical activity and overall cognitive functioning in children (effect size [ES] = 0.21; 8–10 years).[24] Meta-analyses on studies allowing the investigation of causal relationships showed significant positive effects of physical activity on children's executive functions (ES = 0.57; 6–12 years)[12] and academic performance (ES = 0.27; 3–18 years).[4] In these previous meta-analyses only a few intervention studies investigated the causal effects in preadolescent children, especially those intervention studies that implemented a longitudinal physical activity program.[12] More recently, several randomized controlled trials have become available, aimed at investigating the effects of acute physical activity and longitudinal physical activity programs on cognitive functioning in preadolescent children.[20,25,26]

The current meta-analysis updates and expands previous meta-analyses by including only studies that investigate the effects of acute physical activity or longitudinal physical activity programs with an appropriate control group. All correlational studies were excluded from the present meta-analysis, as these designs do not allow investigation of causal effects. In addition, uncontrolled studies were excluded, because these designs do not allow conclusions on whether the possible improvements would also have been found if the participants had been exposed to another intervention not involving physical activity.[27] The aim of the present meta-analysis is to provide a systematic review of all available studies that investigated the effects of physical activity on multiple domains of executive functions, attention and academic performance in preadolescent children. In addition, a systematic quantification of the effects of physical activity on these domains is provided.

2. Methods

The electronic databases PubMed, Web of Science, MEDLINE and ERIC were searched for studies that investigated the effects of physical activity on attention, executive functions and/or academic performance. Key search terms included the words physical activity, physical fitness, executive functions, cognition, academic performance and children. Medical Subject Headings (MeSH) terms, free text words and all possible equivalents were used (Table 1S, see Supplementary material). The current meta-analysis included all studies that: (a) investigated the effects of physical activity on executive functions, attention and/or academic performance, (b) were written in the English language and published between 2000 and April 2017, (c) focused on primary school children between the age of 6–12 years, (d) included a random assignment or matching with appropriate adjustments for any pre-test differences[28] and (e) included outcome variables measuring executive functions, attention or academic performance on interval- or ratio-level scale. Exclusion criteria for the current meta-analysis were: (a) studies targeting special populations (e.g. children with mental or cognition disorders, nervous system diseases or brain injuries), (b) studies without appropriate control conditions or groups[29] and (c) studies of which the intervention consisted of more than just specific physical activity (e.g. interventions that included physical active and cognitive tasks). The PRISMA-statement for reporting systematic reviews and meta-analysis was used as a guideline to conduct the review.[30] A trained research assistant screened the titles of all studies retrieved from the electronic databases for potentially suitable studies, after which the trained research assistant and the first author screened the abstracts of the selected studies. If there was a doubt about the suitability of the study based on the abstract, the authors assessed the eligibility based on the full text of the article. The reference list of relevant reviews were searched for additional studies. Lead authors from studies without details that allowed for the calculation of ESs were contacted by email to retrieve missing details.

After removing duplicates and adding 7 studies from previous reviews, our initial electronic search yielded 3032 studies that were reviewed based on their title (Fig. 1). Seventy five (n = 75) full-text articles were reviewed, after which 41 were excluded (Table 2S, see Supplementary material). Common exclusion reasons were: studies without appropriate control conditions or groups (n = 9), cognitive tests that did not explicitly assess executive functions (n = 7), ages of participants were (partly) outside of target age range (n = 7) or interventions that combined physical activity with academic assignments (n = 6). Finally, one study was excluded because additional details were needed to calculate an ES and we received no response on our email nor on our reminder.[31] Thus, a total of 31 studies (4593 children) were included in the meta-analysis. The characteristics of the included studies can be found in Table 3S (see Supplementary material).

The study quality of the selected studies was assessed independently by a research assistant and the first author according to the Physiotherapy Evidence Database (PEDro) scale. The PEDro scale is an 11-item scale which has been used extensively in meta-analyses and reliably assesses randomization, blinding, intention-to-treat, between-group comparison and measures of variability.[32] Scores on the PEDro scale range between 0 and 10 (one item pertains external validity and is not used to calculate the score). An adequate quality is defined as a study having an adequate generation

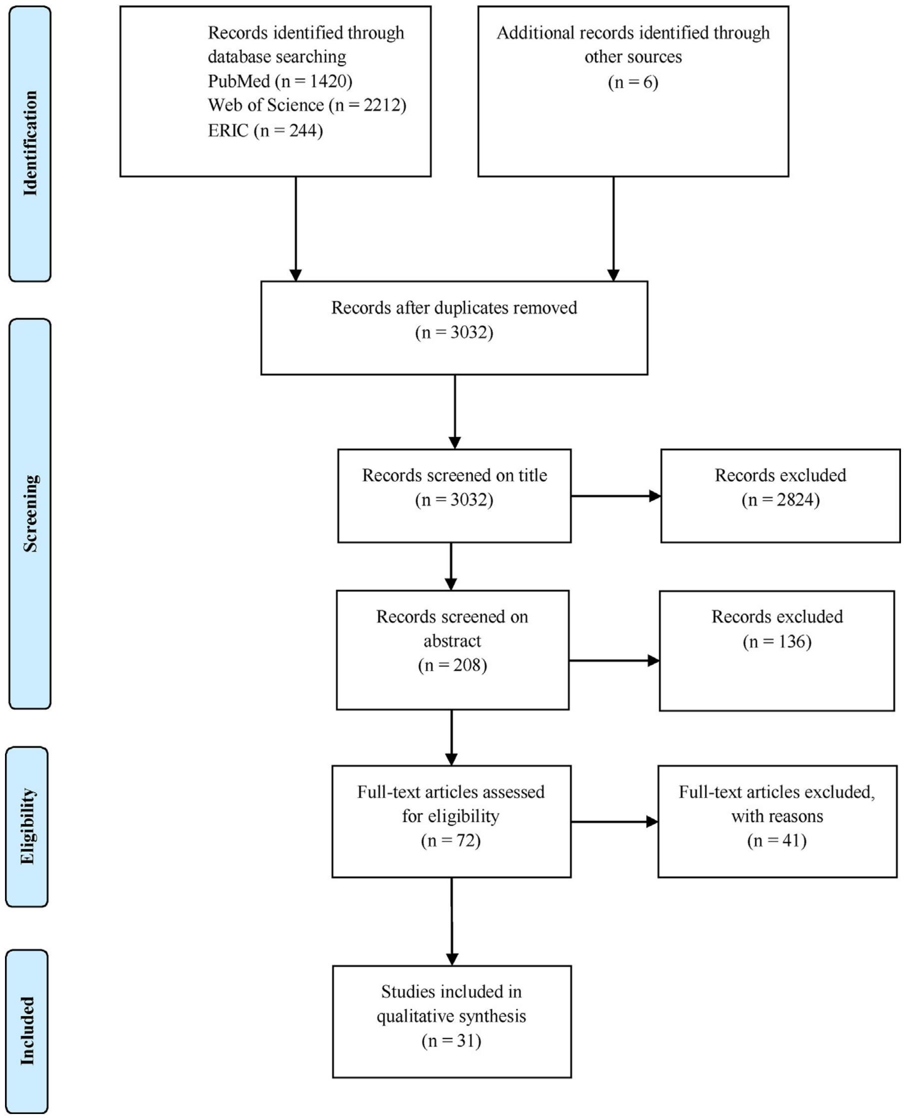


Fig. 1. PRISMA flow diagram of the selection of studies.

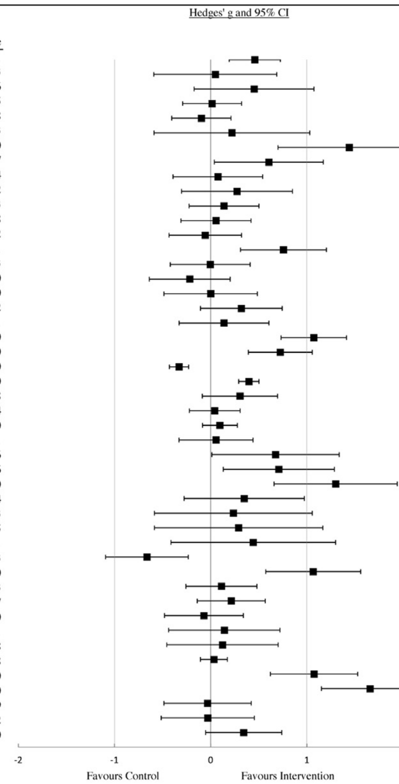
of random sequence, concealment of allocation and blinding of outcome assessors.[33] This is represented by a PEDro summary score of at least 5 points.[33] Discrepancies regarding study quality were discussed until consensus was reached.

Statistical analysis was performed using Comprehensive Meta-Analysis (version 2.2). First, studies were coded in terms of study design, distinguishing between studies investigating acute physical activity or a longitudinal physical activity program. Secondly, primarily for the purpose of the aim, three separate meta-analyses were conducted for the domains executive functions, attention and academic performance. Third, a subgroup analysis was conducted for several subdomains. Four subdomains of executive functions were distinguished: inhibition, working memory, cognitive flexibility and planning. These subdomains were chosen because they are relatively easy to operationalize and are likely to be implicated in the performance of the tests used in most of the included studies.[6,34,35] Three subdomains of attention were distinguished: selective, divided and sustained.[36] In addition, three subdomains of academic performance were distinguished: mathematics, spelling and reading. Fourth, two additional meta-analysis were conducted for aerobic and cognitively engaging physical activity. Last, a meta-regression was conducted to investigate the effects of duration for acute physical activity (in minutes) and for the longitudinal physical activity program (in weeks).

No statistical comparisons were made between the domains and subdomains because data from multiple domains and subdomains came from the same children making it unlikely that the assumption of independence was true. To control for dependency between multiple outcome variables (e.g. accuracy and reaction time) within a subdomain (e.g. inhibition), a mean ES of the outcome variables was used. In case of multiple independent subgroups within a study (e.g. multiple intervention groups), subgroup was used as the unit of analysis. To adjust for respective sample sizes, Hedges' adjusted g was used and studies were weighted by the study inverse variance. The magnitude of Hedges' g was interpreted using Cohen's guidelines, distinguishing between small (<0.2), moderate (0.5), and large (>0.8) ESs.[37] We used a random effects approach to compute overall ESs.[38] Several studies collected data at multiple points. In such cases, only the baseline scores and the scores closest to the end of the intervention were used to calculate the ES. Heterogeneity of each effect was assessed using the I^2 and Q statistics.[38] The presence of a publication bias for executive functions, attention and academic performance was assessed by using a funnel plot, calculating the Rosenthal's fail-safe N and performing the Egger's linear regression method. The moderation effect of duration was inves-

Table 1
Individual effect sizes for each subgroup within the included studies.

Study name	Subgroup within study	Comparison	Outcome	Statistics for each study						
				Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Ahamed et al.[55]	Blank	Academic	CAT-3	0.459	0.136	0.018	0.193	0.725	3.379	0.001
Altenburg et al.[25]	Group B	Selective attention	Sky Search Score	0.048	0.326	0.107	-0.592	0.688	0.148	0.883
	Group C	Selective attention	Sky Search Score	0.451	0.318	0.101	-0.172	1.075	1.420	0.156
Best[39]	High CE	Inhibition	Combined	0.015	0.157	0.025	-0.292	0.322	0.094	0.925
	Low CE	Inhibition	Combined	-0.097	0.157	0.025	-0.405	0.211	-0.616	0.538
Chaddock-Heyman et al.[56]	Blank	Inhibition	Combined	0.221	0.413	0.171	-0.589	1.031	0.535	0.593
Chen et al.[40]	3rd grade	Combined	Combined	1.442	0.379	0.143	0.700	2.185	3.808	0.000
	5th grade	Combined	Combined	0.605	0.289	0.084	0.038	1.172	2.091	0.037
Crova et al.[57]	Blank	Combined	Combined	0.075	0.238	0.056	-0.391	0.540	0.314	0.754
Dalziell et al.[58]	Blank	Combined	Combined	0.274	0.294	0.086	-0.303	0.850	0.931	0.352
Davis et al.[59]	High	Combined	Combined	0.139	0.185	0.034	-0.224	0.501	0.751	0.453
	Low	Combined	Combined	0.055	0.185	0.034	-0.309	0.418	0.296	0.768
Drollette et al.[41]	Higher performers	Inhibition	Combined	-0.056	0.192	0.037	-0.433	0.321	-0.289	0.772
	Lower performers	Inhibition	Combined	0.757	0.228	0.052	0.310	1.204	3.316	0.001
Duncan & Johnson[42]	Moderate	Combined	WRAT 4	-0.005	0.212	0.045	-0.420	0.411	-0.022	0.983
	Vigorous	Combined	WRAT 4	-0.218	0.215	0.046	-0.639	0.203	-1.015	0.310
Fisher et al.[60]	Blank	Planning	CAS	0.000	0.247	0.061	-0.485	0.485	0.000	1.000
Gallotta et al.[43]	CPE	Selective attention	D2	0.319	0.217	0.047	-0.106	0.745	1.470	0.142
	PE	Selective attention	D2	0.139	0.238	0.057	-0.328	0.606	0.582	0.561
Gallotta et al.[61]	Coordinative PA	Selective attention	D2	1.072	0.173	0.030	0.732	1.412	6.183	0.000
	Traditional PA	Selective attention	D2	0.724	0.170	0.029	0.391	1.056	4.263	0.000
Hill et al.[44]	Group A	Working memory	Combined	-0.329	0.051	0.003	-0.429	-0.229	-6.443	0.000
	Group B	Working memory	Combined	0.397	0.054	0.003	0.292	0.502	7.423	0.000
Hillman et al.[45]	Blank	Combined	Combined	0.304	0.199	0.040	-0.087	0.694	1.524	0.128
Hillman et al.[26]	Blank	Combined	Combined	0.042	0.135	0.018	-0.222	0.306	0.314	0.754
Howie et al.[46]	Blank	Combined	Combined	0.096	0.092	0.008	-0.085	0.276	1.037	0.300
Jäger et al.[47]	Blank	Combined	Combined	0.055	0.196	0.038	-0.330	0.439	0.278	0.781
Kamijo et al.[62]	Blank	Working memory	Sternberg	0.674	0.337	0.114	0.012	1.335	1.997	0.046
Koutsandréou et al.[63]	Cardiovascular exercise	Working memory	Number of correct responses	0.709	0.295	0.087	0.131	1.288	2.403	0.016
	Motor exercise	Working memory	Number of correct responses	1.300	0.327	0.107	0.659	1.941	3.973	0.000
Krafft et al.[65]	Blank	Inhibition	Combined	0.349	0.319	0.102	-0.276	0.974	1.094	0.274
Krafft et al.[64]	Blank	Other	CAS	0.236	0.419	0.175	-0.585	1.056	0.563	0.573
Niemann et al.[48]	High active	Selective attention	D2	0.291	0.447	0.199	-0.585	1.166	0.651	0.515
	Low active	Selective attention	D2	0.443	0.437	0.191	-0.413	1.299	1.014	0.311
Pirrie & Lodewyk[49]	PA-resting	Combined	Combined	-0.663	0.219	0.048	-1.093	-0.233	-3.020	0.003
	Resting-PA	Combined	Combined	1.066	0.252	0.064	0.572	1.561	4.228	0.000
Schmidt et al.[20]	Aerobic exercise	Combined	Combined	0.112	0.188	0.035	-0.257	0.480	0.593	0.553
	Team games	Combined	Combined	0.214	0.180	0.033	-0.140	0.567	1.184	0.237
Schmidt et al.[50]	Blank	Selective attention	D2	-0.070	0.210	0.044	-0.480	0.341	-0.332	0.740
Schmidt et al.[51]	Combo group	Selective attention	D2	0.142	0.295	0.087	-0.437	0.720	0.480	0.631
	Physical group	Selective attention	D2	0.123	0.295	0.087	-0.456	0.701	0.416	0.678
Thompson et al.[52]	Blank	Combined	NWEA	0.033	0.071	0.005	-0.107	0.172	0.456	0.648
Tine & Butler[53]	High-income	Selective attention	D2 TN	1.075	0.232	0.054	0.621	1.528	4.641	0.000
	Low-income	Selective attention	D2 TN	1.658	0.258	0.067	1.152	2.165	6.420	0.000
Tomporowski et al.[54]	Older	Cognitive flexibility	Combined	-0.032	0.231	0.054	-0.486	0.421	-0.140	0.889
	Young	Cognitive flexibility	Combined	-0.030	0.247	0.061	-0.515	0.454	-0.123	0.902
van der Niet et al.[66]	Blank	Combined	Combined	0.343	0.202	0.041	-0.053	0.739	1.698	0.090



tigated with a fixed effects meta-regression analysis. Statistical significance was adopted for all tests when $p < 0.05$.

3. Results

The ESs of the individual studies can be found in Table 1. The funnel plot resembled a funnel and the Egger's linear regression method was non-significant for executive functions, attention and academic performance indication that there was no evidence of publication bias. There were however considerable differences between the ESs derived from the individual studies [$I^2 = 84\%$; $Q = 286.87$; $p < 0.001$]. The mean PEDro score was 4.3 (below adequate) and had a range between 2 (below adequate) and 7 (adequate) (Table 3S, see Supplementary material).

Seventeen studies (s = 17) were included that examined the effects of acute physical activity on cognitive functions [$I^2 = 87\%$; $Q = 217.18$; $p < 0.001$], which resulted in a total of 29 comparisons (k = 29).[25,39–54] Of these studies, 10 (59%) reported positive findings on at least one of the outcome measures,[25,40–42,44–48,53] six studies (35%) reported no significant findings[39,49–52,54] and one study (6%) reported a negative finding.[43] Overall, acute physical activity resulted in a small to moderate improvement of cognitive functions [Hedges' g = 0.24; 95% CI = 0.08, 0.40; p = 0.004] (Table 2).

No significant effect was found for acute physical activity on executive functions (s = 9, k = 15). When looking at the subdomains of executive functions, a small to moderate positive effect of acute physical activity was found for inhibition [Hedges' g = 0.28; 95% CI = 0.01, 0.56; p = 0.042]. No significant effect was found for working memory (s = 4, k = 6) or cognitive flexibility (s = 5, k = 8). No studies investigated the effects of acute physical activity on planning.

Six studies focused on the effects of acute physical activity on selective attention (k = 11),[25,43,48,50,51,53] with considerable differences between the ESs [$I^2 = 76\%$; $Q = 41.31$; $p < 0.001$]. No studies focused on sustained or divided attention. Overall, acute physical activity resulted in a small to moderate improvement of selective attention [Hedges' g = 0.43; 95% CI = 0.09, 0.77; p = 0.013].

No overall significant effect was found for acute physical activity on academic performance (s = 4, k = 5), with minor differences between the studies [$I^2 = 26\%$; $Q = 5.39$; $p = 0.250$].[42,45,46,52] Investigating each distinguished subdomain of academic performance, a small to moderate effect was found for spelling [Hedges' g = 0.25; 95% CI = 0.03, 0.48; p = 0.030] (s = 2, k = 3).[42,45] No significant effects were found for mathematics (s = 4, k = 5)[42,45,46,52] and reading (s = 3, k = 4).[42,45,52]

Of the studies that investigated the effects of acute physical activity, 15 studies (k = 24) focused on the effects of aerobic physical activity, resulting in a small to moderate positive effect [Hedges' g = 0.28; 95% CI = 0.09, 0.46; p = 0.004].[25,39–46,48,49,51–54] Five studies (k = 5) focused on the effects of cognitively engaging physical activity which showed no significant effect.[39,43,47,50,51] To include all studies in the meta-regression, a correction on the standard errors (dividing the standard error by the square root of the number of comparisons) was applied for one study that used different durations of acute physical activity.[46] Duration (in minutes) had no significant influence on the effects of acute physical activity ($\beta < 0.001$; p = 907).

Fourteen included studies (k = 18) implemented a longitudinal physical activity program and examined the effects on cognitive functions [$I^2 = 65\%$; $Q = 48.46$; $p < 0.001$].[20,26,55–66] Nine of these studies (64%) reported positive findings on at least one of the outcome measures,[20,26,56,58,59,61–63,66] five studies (36%) reported no significant finding[55,57,60,64,65] and no studies reported a negative finding. Longitudinal physical activity programs resulted in an overall small to moderate improvement of cognitive functions [Hedges' g = 0.37; 95% CI = 0.20, 0.55; $p \leq 0.001$].

Table 2
Meta-analytic results with potential moderators affecting the effects of physical activity on cognitive performance.

	Sample size	k	Meta-analytic effect size			Heterogeneity		
			Hedges' g	95% CI	p-value	I^2	Q	p-value
Acute physical activity	2827	29	0.24	[0.08, 0.40]	0.004	87.11	217.18	<0.001
Domains								
Executive functions	1384	15	0.20	[−0.04, 0.42]	0.096	91.03	156.02	<0.001
Inhibition	349	10	0.28	[0.01, 0.56]	0.042	77.64	40.25	<0.001
Working memory	1084	6	0.27	[−0.12, 0.66]	0.176	95.88	121.38	<0.001
Cognitive flexibility	458	8	0.30	[−0.14, 0.73]	0.182	88.29	59.80	<0.001
Planning	–	–	–	–	–	–	–	–
Attention	616	11	0.43	[0.09, 0.77]	0.013	75.79	41.31	<0.001
Academic performance	941	5	0.09	[−0.05, 0.22]	0.196	25.76	5.39	0.250
Mathematics	941	5	−0.18	[−0.48, 0.13]	0.254	84.27	25.42	<0.001
Reading	847	4	0.17	[−0.08, 0.41]	0.185	57.75	7.10	0.069
Spelling	56	3	0.25	[0.03, 0.48]	0.030	<0.01	0.52	0.772
Type of physical activity								
Aerobic	2472	24	0.28	[0.09, 0.46]	0.004	89.31	215.21	<0.001
Cognitively engaging	355	5	0.07	[−0.11, 0.25]	0.424	<0.01	1.95	0.745
Longitudinal physical activity	1766	18	0.37	[0.20, 0.55]	<0.001	64.92	48.46	<0.001
Domains								
Executive functions	1179	15	0.24	[0.09, 0.39]	0.001	34.00	21.21	0.096
Inhibition	688	7	0.19	[−0.04, 0.42]	0.097	49.72	11.93	0.063
Working memory	579	8	0.36	[0.10, 0.62]	0.007	56.79	16.20	0.023
Cognitive flexibility	556	4	0.18	[0.01, 0.35]	0.040	4.79	3.15	0.369
Planning	394	4	0.12	[−0.08, 0.32]	0.224	<0.01	0.78	0.855
Attention	299	2	0.90	[0.56, 1.24]	<0.001	51.49	2.06	0.151
Academic performance	565	4	0.26	[0.02, 0.49]	0.032	38.84	4.91	0.179
Mathematics	231	2	0.09	[−0.17, 0.35]	0.490	<0.01	<0.01	0.983
Reading	277	3	0.15	[−0.15, 0.46]	0.316	35.31	3.10	0.213
Spelling	46	1	0.34	[−0.23, 0.92]	0.243	–	–	–
Type of physical activity								
Aerobic	1231	12	0.29	[0.13, 0.45]	0.001	43.23	19.38	0.055
Cognitively engaging	535	6	0.53	[0.14, 0.92]	0.008	78.87	23.67	<0.001

Note: k = number of comparisons.

A small to moderate positive effect was found for longitudinal physical activity programs on executive functions [Hedges' g = 0.24; 95% CI = 0.09, 0.39; p = 0.001] (s = 12, k = 15).[20,26,56–60,62–66] Investigating the subdomains of executive functions, a small to moderate positive effect was found for working memory [Hedges' g = 0.36; 95% CI = 0.10, 0.62; p = 0.007] (s = 6, k = 8)[20,57,58,62,63,66] and a small positive effect was found for cognitive flexibility [Hedges' g = 0.18; 95% CI = 0.01, 0.35; p = 0.040] (s = 3, k = 4).[20,26,66] No significant effects of longitudinal physical activity programs were found for inhibition (s = 6, k = 7)[20,26,56,57,65,66] and planning (s = 4, k = 4).[59,60,64,66]

One study (k = 2) found a large positive effect of a longitudinal physical activity program on selective attention [Hedges' g = 0.90; 95% CI = 0.56, 1.24; p = < 0.001].[61] No studies focused on sustained or divided attention.

Three studies (k = 4) focused on the effects of a longitudinal physical activity program on academic performance, with minor differences between the studies [I^2 = 39%; Q = 4.91; p 0.179].[55,58,59] An overall small to moderate positive effect was found on academic performance [Hedges' g = 0.26; 95% CI = 0.02, 0.49; p = 0.032]. However, investigating each distinguished subdomain of academic performance, no significant effects of longitudinal physical activity were found for mathematics (s = 1, k = 2),[59] reading (s = 2, k = 3)[58,59] and spelling (s = 1, k = 1).[58]

Investigating the type of physical activity within studies that implemented a longitudinal physical activity program, 11 studies (k = 12) focused on aerobic physical activity[20,26,55,56,59–65] and five studies (k = 6) focused on cognitively engaging physical activity.[57,58,61,63,66] A small to moderate positive effect was found for aerobic [Hedges' g = 0.29; 95% CI = 0.13, 0.45; p = 0.001] and a moderate to large positive effect for cognitively engaging physical activity [Hedges' g = 0.53; 95% CI = 0.14, 0.92; p = 0.008]. Duration (in weeks) had no significant influence on the effects of longitudinal physical activity programs (β < 0.001; p = 0.952).

4. Discussion

The current meta-analysis investigated the effects of physical activity on executive functions, attention and academic performance in preadolescent children based on the outcome data of 31 studies. The meta-analysis showed that acute physical activity has a positive small to moderate effect on attention (ES = 0.43), while longitudinal physical activity programs has a positive small to moderate effect on executive functions (ES = 0.24), a positive large effect on attention (ES = 0.90) and a positive small to moderate effect on academic performance (ES = 0.26).

This meta-analysis expanded the evidence by examining the results of 9 recent studies that aimed to investigate the effects of acute physical activity on executive functions in preadolescent children. For acute physical activity (i.e. a single bout of physical activity), no effect was found in the current meta-analysis, while a moderate to large positive effect (ES = 0.57; s = 2) was found in Verburgh et al.[12] The reason for this difference is likely due to the inclusion of a larger number of studies in the current meta-analysis (s = 9) which may reflect a more reliable result. Despite the inclusion of a large number of studies, still large ES differences between studies were found. The effects largely depend on different moderators, such as outcome measure,[40,41,45,49] duration[46] or effects were only found in a subgroup.[39,41,44] The positive small to moderate effect of acute physical activity on attention (ES = 0.43) is comparable with the small to moderate effect found in the meta-analysis by Chang et al.[8] (ES = 0.42). These findings are in accordance with the hypothesis that acute physical activity immediately facilitates the cognitive performance by increasing the allocation of attention.[13,14] The combined finding that acute physical activity has an effect on attention and inhibition (ES = 0.28), while no effect on other domains of executive functions (e.g. working memory, cognitive flexibility and planning) supports the hypothesis that attentional problems in children are related with specific domains of executive functions, particularly with inhibition.[10] In addition, the positive effects on attention are expected to increase the time children are engaged in academic subjects,[67] with better academic performance in the long term.

For longitudinal physical activity programs (i.e. continuous regular physical activity over several weeks), a positive small to moderate effect on executive functions (ES = 0.24) was found, which is slightly lower than the positive small to moderate effect on executive functions (ES = 0.46) found in a previous meta-analysis including both children and adolescents.[22] Verburgh et al.[12] found no significant effect of longitudinal physical activity programs (s = 3), which might be explained by the inclusion of a larger number of studies in the current meta-analysis (s = 12). With regard to academic performance, a small to moderate effect of longitudinal physical activity programs was found (ES = 0.26). These effects are similar with the small to moderate effects found by Fedewa and Ahn[4] (ES = 0.27). There is an increasing pressure to reduce time in the school curriculum for physical education, in order to make room for learning academic skills such as spelling, mathematics and reading. It is therefore important to acknowledge the positive effect of physical activity on academic performance.[68] Interestingly, the meta-analysis by Fedewa and Ahn[4] found the highest effect on mathematics and closely followed by reading, while no effect was found on any of the subdomains (mathematics, reading and spelling) in the current meta-analysis. It seems unlikely that this difference is explained because of an age difference, since Fedewa and Ahn[4] found the highest ESs on academic performance for children at the elementary school level, compared with the middle and high school levels. By focusing only on preadolescent children, the number of studies per subdomain of academic performance in the current meta-analysis was low. Therefore, the results of the subdomains of academic performance should be interpreted with caution and possibly explaining the differences between the current results and the ones found by Fedewa and Ahn.[4]

Interestingly, the longitudinal physical activity programs that focused on cognitively engaging physical activity (s = 11) showed a moderate to large positive effect (ES = 0.53), while aerobic physical activity showed a small to moderate positive effect (ES = 0.29). For cognitively engaging physical activity, a child has to allocate a high amount of attention and cognitive effort.[23] It is thought that by specifically selecting physical activities with a relatively high cognitive engagement, performance on cognitive functions will increase. Although both types of physical activity showed beneficial effects, the current findings suggests that physical activity with a higher cognitive engagement has more effect on executive functions compared to aerobic physical activity. This finding is supported by the recent meta-analysis that compared the effects of different types of longitudinal physical activity programs on cognitive functioning in children and adolescents.[22] This makes cognitively engaging physical activity an interesting focus for future intervention programs.

Some limitations should be considered before drawing conclusions. First, although different types of moderators that might have influenced the size of the effects of physical activity were investigated, there are additional moderators not included in the current meta-analysis that might have an effect on the physiological responses of physical activity. For example, it is recommended that future studies test different exercise intensities and initial fitness levels. It has been suggested that there is an inverted-U effect with MVPA showing the largest effect on cognition, whereas light and vigorous physical activity showing smaller effects.[69] Nevertheless, almost all studies that focused on the effects of physical activity on cognitive performance in children were conducted with moderate to vigorous intensities.[21] Secondly, the current meta-analysis only included studies that were published after 2000 and that contained a control condition with no or a lower amount of physical activity. Although this resulted in excluding only a small amount of studies, the inclusion of these studies would limit the generalizability of our findings. Including different types of control conditions would require additional comparisons, for which we would like to refer to a recent meta-analysis by Vazou et al.[22]

5. Conclusions

Based on the results of the current meta-analysis positive effects were found for both acute physical activity as well as for longitudinal physical activity programs on cognitive functions (in the current study a combined effect of the domains executive functions, attention and academic performance) in preadolescent children. The positive effects of acute physical activity were only found for attention, while the positive effects of longitudinal physical activity programs were consistent for all domains. The results indicate that benefits are largest for continuous cognitively engaging physical activity over several weeks.

Practical implications

- Single bout of physical activity can be a successful strategy to stimulate attention, but not executive functions or academic performance in children between the age of 6 and 12 years.
- Intervention programs that implement continuous regular physical activity over several weeks are more likely to improve executive functions and academic performance than a single bout of physical activity.
- Interventions programs over several weeks that include cognitively challenging physical activities seem to be more effective in improving cognitive performance than aerobic physical activity.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jsams.2017.09.595.

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[1] Asterisks have been added to those references referring to studies included in the current meta-analysis.

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