The effect of physical activity interventions on executive functions in children with ADHD

Citation for published version:
Welsch, L, Alliott, O, Kelly, P, Fawkner, S, Booth, JN & Niven, A 2021, 'The effect of physical activity interventions on executive functions in children with ADHD: A systematic review and meta-analysis', *Mental Health and Physical Activity*, vol. 20. https://doi.org/10.1016/j.mhpa.2020.100379

Digital Object Identifier (DOI):
10.1016/j.mhpa.2020.100379

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Mental Health and Physical Activity

The effect of physical activity interventions on executive functions in children with ADHD: A systematic review and meta-analysis

Livia Welsch [a] *livia.viva@googlemail.com* (corresponding author)[1]

Dr. Ailsa Niven [a] *ailsa.niven@ed.ac.uk*

Olivia Alliott [b] *olivia.Alliott@mrc-epid.cam.ac.uk*

Dr. Paul Kelly [a] *p.kelly@ed.ac.uk*

Dr. Samantha Fawkner [a] *s.fawkner@ed.ac.uk*

Dr. Josie Booth [a] *josie.Booth@ed.ac.uk*

[a] University of Edinburgh, Moray House School of Education and Sport, University of Edinburgh (Holyrood Campus), EH8 8AQ, Scotland

[b] MRC Epidemiology Unit, University of Cambridge School of Clinical Medicine, Box 285 Institute of Metabolic Science, Cambridge Biomedical Campus, Cambridge CB2 0QQ, England

Conflict of interest: *none*

Funding: *This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.*

---

[1] Change of address since research was conducted: Institut für Psychologische Psychotherapie und Beratung Berlin e.V., Jenaer Str. 7, 10717 Berlin, Germany

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Keywords: inhibition, working memory, attention, shifting, ADHD, exercise therapy

Introduction

Attention-deficit/ hyperactivity disorder (ADHD) is defined as a consistent pattern of inattention, impulsivity and/ or hyperactivity (American Psychiatric Association, 2013). With global prevalence rates between 3-7% it is one of the most commonly diagnosed behavioural disorders in school-aged children (Ahmed & Mohamed, 2011; Smith, 2013). Children with ADHD often exhibit difficulties in several areas including motor skills and academic attainment, and are at a higher risk of comorbidities such as depression, anxiety or developmental coordination disorder than neurotypically developing children (Barnard-Brak, Davis, Sulak, & Brak, 2011; Kiluk, Weden, & Culotta, 2009; O'Neill, Berwid, & Bédard, 2016; Vysniauske, Verburgh, Oosterlaan, & Molendijk, 2016).

One of the core symptoms of ADHD is impaired executive functions (EF; Barkley, 1997), which is a multi-componential construct, including distinct though interrelated cognitive processes necessary to perform difficult or new tasks (Best, 2010). EFs are associated with the prefrontal cortex (PFC; Invernizzi, Crotti, Bosio, Scurati, & Lovecchio, 2018). These processes include inhibition, working memory, shifting, and attention (Diamond, 2013). Inhibition is defined as the control of one's attention, behaviour, thoughts and emotions by overriding internal predisposition or external lures (Diamond, 2013). The working memory describes the aspect of holding information in the mind and working with it mentally (Baddeley & Hitch, 1974), e.g. thinking of a response while listening in a conversation. Shifting means the flexibility to adjust to changed demands or priorities (Diamond, 2013). Finally, attention is the ability to focus on information for several seconds, thus is closely interrelated with working memory (Diamond, 2013).

Given the prevalence, symptoms and co-morbidities for children with ADHD, there is a need for effective treatment. The most commonly used treatments include pharmaceutical approaches, such as methylphenidate (MPH), or therapy aimed at behavior deficits (Barnard-Brak et al., 2011; M. Smith, 2013; Tantillo, Kesick, Hynd, & Dishman, 2002). However, there are limitations to these approaches as they are expensive, burdensome for the participants, and lack long-term noticeable effects (Cornelius, Fedewa, & Ahn, 2017; Molina et al., 2009); nor are they continuously applied over 24 hours, resulting in diagnosed children being untreated for periods at a time (Cornelius et al., 2017). They can also lead to negative physical symptoms such as insomnia, head- and stomach-ache, increased blood pressure and heart-rate as well as decreased appetite (Smith & Shapiro, 2015). The necessity for other intervention options as independent or adjunct therapies is thus apparent (Smith, 2013; Vysniauske et al., 2016).

Physical activity (PA) may be a feasible, sustainable, and relatively low cost alternative or complementary treatment for ADHD with longer-term effects (Cornelius et al., 2017). Several studies on both primary and review level have shown beneficial effects of PA interventions on core symptoms of ADHD in children (Cornelius et al., 2017; Suarez-Manzano, Ruiz-Ariza, De La Torre-Cruz, & Martínez-López, 2018; Vysniauske et al., 2016). These data are further supported by review evidence that PA interventions have a positive effect on EF in neurotypically developing children (Álvarez-Bueno et al., 2017; De Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2017; Verburgh, Königs, Scherder, & Oosterlaan, 2014). In addition to specific benefits relating to ADHD, a particularly appealing feature of PA is its potential to reduce ADHD comorbidities, such as depression and anxiety (Kiluk et al., 2009). Additionally, a bidirectional relationship has been found between decreased attention deficits, increased cognitive functions and social competency following PA (Bailey, 2006; Barnard-Brak et al., 2011; Diamond, 2000). PA thus has the potential to decrease social difficulties often experienced by children with ADHD by providing a setting in which social interactions emerge naturally (Bailey, 2006; Barnard-Brak et al., 2011; Kang, Choi, Kang, & Han, 2011; Verret, Guay, Berthiaume, Gardiner, & Béliveau, 2012).

However, there is lack of consensus on the valence and size of the effect of PA on EF in children with ADHD (Cornelius et al., 2017; Suarez-Manzano et al., 2018; Vysniauske et al., 2016). Critically, prior systematic reviews have also failed to investigate the effect of chronic (i.e. sustained) PA on EF in children with ADHD, nor explored the effect on the various distinct, though interrelated, processes of EF (i.e., inhibition, working memory, shifting and attention; Best, 2010). Each of these components of EF follow a unique developmental trajectory (Best, 2010), and thus PA may impact each component differently, with some likely to be more sensitive to PA than others.

ADHD is demonstrated to have a multi-causal etiology with the interaction of numerous factors resulting in neurobiological differences (Brock, Jimerson, & Hansen, 2009a). Thus, not surprisingly, PA may influence cognitive functions via different pathways. Highly cognitively demanding PA has been assumed to activate multiple pathways simultaneously thus showing greater impact for children with ADHD (Best, 2010). Indeed, higher cognitively engaging PA programs have been found to be more effective for improving cognitive functions of children who are neurotypically developing, and those with ADHD (Álvarez-Bueno et al., 2017; Cerrillo-Urbina et al., 2015; van der Fels et al., 2015). Cognitive demand is thus worthy of consideration when investigating different EF domains. High cognitively demanding PA may include fine motor skills, bilateral body coordination or timed movement performance (van der Fels et al., 2015) and can be classified using the concept of contextual interference. That is, a higher demand is placed on executive processes due to creating, monitoring and modifying an action plan in the presence of constantly changing task demands (Brady, 2008).

Another pathway in which PA may affect ADHD symptoms includes the increase of dopaminergic and norepinephrine neurotransmission (Barnard-Brak et al., 2011; O’Neill et al., 2016), similar to the effect induced by MPH (Cerrillo-Urbina et al., 2015). Janssen et al. (2016) compared PA to MPH, the latter resulting in greater benefit for children with ADHD. The supremacy of MPH is of no surprise as ADHD medication was specifically designed to increase catecholamine levels (Brock, Jimerson, & Hansen, 2009b). This finding could suggest that the effect of MPH may mask beneficial effects of PA on EFs, and therefore further consideration of the moderating effect of MPH is warranted.

There has been limited consideration however of the influence of moderators such as physical activity type specifically regarding cognitive demand, and MPH intake on EF processes. Therefore, the aims of this review are to examine the effect of chronic PA interventions on EF domains (inhibition, shifting, working memory, attention) in children with ADHD compared to no treatment control groups, and consider the differential effect of both cognitive demand of PA and MPH-intake on the relationship between PA and EF in children with ADHD.

Methods

This systematic review followed the Cochrane Guidelines for Systematic Reviews (Higgins & Green, 2011) and the PRISMA Checklist (Liberati et al., 2009; supplementary material *S1*). A study protocol was published with PROSPERO (CRD42018099617; Welsch, Alliott, Fawkner, & Niven, 2018).

Search Strategy

The data bases Web of Science, PsycINFO, SPORTDiscus, ERIC, PubMed, British Education Index and Physical Education Index were searched on June 11th-13th 2019 for studies without any restrictions regarding publication date. The search strategy included terms describing the categories of intervention, the condition, study population and outcomes (*table 1*). Additional studies were identified by screening the systematic reviews and meta-analyses included in the search results. All studies identified in the search were imported into Covidence for further screening.

Eligibility criteria

Studies meeting the following criteria were included: a) randomized controlled studies, quasi-experimental studies, uncontrolled pre-post studies, b) intervention design with PA programs testing effects of physical activity intervention on EFs compared to no intervention, c) studies comparing different types of chronic PA interventions, d) samples consisted of children (0-18 years) diagnosed with ADHD or any subtype according to ICD-10 or any DSM by a professional or on a validated rating scale, e) outcomes measuring EFs, f) studies were published in English. Studies were excluded when a) the intervention was defined by a single bout of PA, b) participants had diagnosed comorbidities including physical conditions impeding participation in PA programs, c) effectiveness of PA intervention could not be established due to multi-component interventions, d) outcomes only measured changes in physical, aerobic or gross motor abilities.

Screening

After excluding any duplicates, retrieved studies were screened for title and abstract in a first stage, and full articles were then located for the studies subsequently included. Title and abstract and the ensuing full text screening were undertaken by two researchers. Conflicts in either stage were resolved through discussion between both researchers. The screening process is represented in a PRISMA flow chart (*figure 1*).

Data extraction

Data from the included studies were extracted onto an excel spreadsheet designed for this review. Extracted data included characteristics of the study design, sample population and PA interventions. Statistical results necessary to calculate effect sizes (ES) were obtained including means (*m*) of the pre- and post-measures and standard deviation (*SD*) of post-measures for experimental and control groups. Authors were contacted via E-Mail for those studies in which necessary values for the analysis (e.g. ES or post-measure outcome) were not reported.

Bias Assessment

The quality of the studies was assessed with the Cochrane Collaboration's tool for assessing risk of bias (Higgins & Green, 2011) and followed the published guidelines with the following interpretations: Sequence generation was assessed as low risk for all studies using a randomized sample; the risk for bias due to unblinded assessors was rated low for measures such as objective measures or computerized tests; any studies missing data or not reporting precise outcome results, but merely stating non-significance of results were rated as high risk for reporting bias; domains regarding outcomes and measures were only rated for those measuring executive functions. Blinding of participants and personnel was rated high across all studies as the participants taking part in a PA intervention cannot be blinded.

Effect size calculation

Scales were inverted where beneficial changes in EF outcomes were indicated by a decrease in scores to standardize the direction of the effect across all included studies. The sample size of the shared group of studies with two intervention groups and one control group was halved in the meta-analysis to avoid unit-of-analysis errors (Higgins & Green, 2011). The standardized mean differences (*SMD*) were calculated using mean differences (*MD*) resulting from the difference of pre- and post-measures divided by the post-measure *SD* for each group separately.

Statistical Analysis

Separate meta-analyses were conducted for the different processes of EFs. Outcome measures indicating EF were divided into psychometrics tests measuring inhibition, shifting, working memory and attention. These groups were specified post-hoc according to data in primary studies. One ES from each EF domain was chosen from each study for further analysis as recommended by Cumming (2012), while not all studies included all EF domains (e.g. Memarmoghaddam et al. (2016) only included outcomes measuring inhibition). Outcomes extracted for each EF domain were based on those most consistently reported across primary studies to minimize heterogeneity.

Further, subgroup analyses were conducted to investigate the moderating effect of the cognitive demand of the PA intervention and MPH intake of the participants on EF outcomes. For the cognitive demand, studies were divided into subgroups based on the concept of contextual interference (Brady, 2008). High-cognitively demanding activities contained exercises like ball games and explicit training of cognitive functions including sensorimotor and perceptual-motor training. Low-cognitively demanding PA included yoga or purely aerobic interventions. For the second subgroup analysis, studies were divided into groups based on MPH intake vs. no MPH intake in the study population. Differences between the subgroups were tested with the χ^2-test comparing the overall ES.

SPSS Version 24 (IBM Corperation, 2015), was used to analyze the demographic data and calculate mean differences (*MD*). Further steps of the meta-analysis were conducted in Review Manager 5.3 (RevMan 5.3; The Nordic Cochrane Centre, 2014). The analysis was based on the random effects model as high heterogeneity between studies was expected due to the many different outcome measures used (Cumming, 2012). In deviation from the method proposed in the protocol, due to the use of RevMan 5.3 the standardized mean differences (*SMD*) were assessed rather than Hedge's adjusted g, as initially planned.

SMD, 95%-confidence intervals (95%-*CI*) and *p*-values were reported for all overall outcomes. Interpretation of the ES followed Cohen's (1988) guidelines, with negative ES indicating beneficial effects. The significance level was set to $\alpha < 0.05$. Heterogeneity of the studies was assessed with I^2 (Higgins & Thompson, 2002), with interpretation following the Cochrane guidelines (Higgins & Green, 2011). Heterogeneity in study designs (i.e. PA characteristics and various EF measures) was addressed via subgroups and sensitivity analysis to test the influence of differing PA intervention characteristics for each outcome as well as separate meta-analyses for varying EF processes. Forest plots were used to illustrate the results of the meta-analyses. A possible publication bias could not be assessed due to the small number of included studies in each meta-analysis (n < 10; Page, 2018).

Results

Screening

Figure 1 illustrates the PRISMA flow diagram of the selection of eligible studies. The initial search resulted in 4161 studies. Of the eligible studies, authors of two studies provided non-reported data necessary for the analysis (Verret et al., 2012; Ziereis & Jansen, 2015). Data required to calculate effect sizes were however not accessible for one study resulting in the exclusion from further analysis (Kang et al., 2011).

Study Characteristics

Ultimately, 12 studies were included in the meta-analyses, with characteristics summarized in *table 2.* Ziereis & Jansen (2015) compared two experimental groups to a single control group. Thus, data of 13 experimental and 12 control groups were included in the analysis (*table 2*). Overall, data were collected in eight countries (Taiwan (*n* = 4); Iran (*n* = 2); Brazil/ Canada/ Germany/ Korea/ Switzerland / Tunisia (*n* = 1)) with a total of 445 participants (347 boys). All children in the experimental groups (*N* = 13) received some kind of PA intervention: 2 PA interventions were at moderate physical activity level, 3 PA interventions at moderate to vigorous physical activity (MVPA) level while for eight interventions no data on intensity was provided. Two of the studies included flexibility PA interventions in form of yoga, while 10 studies implemented aerobic PA interventions, including the differing interventions of Ziereis & Jansen (2015). In the control groups, participants received no intervention (*N* = 9) or were put on a waiting list (*N* = 3). Demographic data for all studies are presented in *table 3*.

Risk of bias assessment

The results of the risk of bias assessment are included in the forest plots.

Statistical Analysis

Overall, 75 ES were extracted from the included studies with 18 ES reporting on relevant outcomes and therefore included in the meta-analyses according to outcomes (Cumming, 2012; supplementary material *S2*). For all EF domains reliable and valid outcome measures were included in the analyses (*table 2)*: Inhibition (Stroop Test, Simon Task. Continuous Performance Test, Go/ No Go Task and Test of Everyday Attention for Children - Walk/Don´t Walk Task), Shifting (Flanker Task, Trail Making Test, Wisconsin Card Sorting Test), Working Memory (Colour Span Task, Digit Span Task and Hamburg-Wechsler Intelligenztest für Kinder IV – Index Working Memory) and Attention (Discrimination Test and Test of Everyday Attention for Children - Score Test). Five scales of measures in four studies were inverted (Benzing & Schmidt, 2019; Pan et al., 2019; Rezaei, Salarpor Kamarzard, & Najafian Razavi, 2019; Verret et al., 2012). The sample size of the control group was halved for the study comparing two PA groups to a control condition (Ziereis & Jansen, 2015).

Inhibition. Nine studies included outcomes measuring inhibition (Benzing & Schmidt, 2019; Chang, Hung, Huang, Hatfield, & Hung, 2014; Kadri, Slimani, Bragazzi, Tod, & Azaiez, 2019; Lee, Song, & Park, 2017; Memarmoghaddam et al., 2016; Pan et al., 2016, 2019; Rezaei et al., 2019; Verret et al., 2012). The overall effect of chronic PA intervention for these 9 studies showed a medium effect size favouring the intervention (*SMD* = -0.57; 95%-*CI* [-1.19; 0.06]; *p* = 0.08) that was not significant. The 95%-*CI* is compatible with both a large positive effect as well as a small negligible negative effect.

Excluding Rezaei et al. (2019) from the meta-analysis, justified by the differing intervention using Yoga with a focus on flexibility rather than aerobic like the other 8 studies, reveals an overall large effect on inhibition measures (*SMD* = -0.77; 95%-*CI* [-1.35; -0.18]; *p* = 0.01). The 95%-*CI* is compatible with a wide range of positive effects from large to negligible. *Figure 2* and *figure 3* illustrate the forest plots of the meta-analyses including and excluding Rezaei et al. (2019) as well as sub-group analyses. The findings of the moderator analysis indicated a large effect size favouring the high cognitively PA intervention (*SMD* = -0.71; 95%-*CI* [-1.34; -0.08]; *p* = 0.03) that was significant. The 95%-*CI* is compatible with a wide range of positive effects from large to negligible. The subgroup differences were statistically non-significant for cognitive demand. There was further no significant difference between MPH intake groups.

Shifting. Figure 4 illustrates the findings of the meta-analysis for all studies and by cognitive demand subgroup analysis. Three of the included studies comprised outcomes measuring shifting (Benzing & Schmidt, 2019; Da Silva et al., 2019; Pan et al., 2019). Two studies used high-cognitively demanding PA interventions, while Da Silva et al. (2019) used low-cognitively demanding swimming as PA. The large overall effect suggested the intervention was beneficial (*SMD* = -1.58; 95%-*CI* [-3.12; -0.04]; *p* = 0.04). While this was statistically significant, the 95%-*CI* is compatible with a wide range of positive effects from large to negligible. The moderator analysis for cognitive demand showed a statistically significant subgroup difference: $\chi^2 = 17.65$, $df = 1$ ($p < 0.0001$), $I^2 = 94.3\%$ favoring low cognitively demanding PA. All studies included participants taking MPH, thus no moderator effect for MPH was examined.

Working memory. Outcomes measuring working memory were found in 3 of the included studies, of which two reported of MPH-intake in their participants (Benzing & Schmidt, 2019; Ziereis & Jansen, 2015). Detailed results can be found in the forest plots in *figure 5* and *figure 6.* Ziereis & Jansen (2015) used low-cognitively demanding PA in one of their exercise groups as did Rezaei et al. (2019). The overall effect of PA interventions on working memory processes were large (*SMD* = -0.99; 95%-*CI* [-1.80; -0.18]; *p* = 0.02). While this was significant, again the 95%-*CI* was compatible with a wide range of positive effects from large to negligible, as they were in the subgroups low-cognitively demanding PA (*figure 5*) and MPH-free (*figure 6).* Subgroup differences were statistically non-significant in both moderator analyses.

Attention. Two studies included outcomes for attention, both with MPH intake in some of the participants, with Verret et al. (2012) applying high-cognitively demanding PA and Chou et al. (2017) low-cognitively demanding. As illustrated in *figure 7*, the analysis showed a large to medium effect size favouring the intervention that was not significant, with the 95%-*CI* compatible with both large positive and small negative effects (*SMD* = -0.76; 95%-*CI* [-1.93; 0.41]; $p = 0.2$). However low-cognitively demanding PA had a large effect with the 95%-*CI* compatible only with positive effects (*SMD* = -1.32; 95%-*CI* [-1.94; -0.70]; $p < 0.001$), leading to a significant subgroup difference ($\chi^2 = 4.89$; $p = 0.03$).

Discussion

Main findings

The aim of this review was to examine the effect of chronic PA interventions on domains of EF in children with ADHD compared to no treatment control groups, and consider the differential effect of cognitive demand of PA and MPH-intake. From the 12 included studies, the overall effects showed medium to large benefits for PA in all domains, but 95%-*CI* intervals were compatible with a range of large to negligible effects for shifting and working memory. Indeed, all the meta-analyses presented in this review demonstrated wide 95%-*CI* therefore indicating a lack of precision of the results presented. The influence of cognitive demand of the PA had a differential effect depending on the EF domain. Specifically, low cognitively demanding PA showed large effect sizes with the 95%-*CIs* compatible only with positive effects with a wide range from large to negligible of PA on measures of attention, shifting and working memory; whilst high cognitive demand had a large positive effect size on inhibition, with the 95%-*CI* compatible with positive effects only. The differing effects of cognitive demand were statistically significant for both the domains shifting and attention only. For MPH, despite there being a significant effect on working memory for the MPH-free subgroup but not for the MPH subgroup, moderator analysis suggested that MPH intake did not impact on the magnitude of the effect.

Findings by EF domains

Inhibition. From nine studies, the overall effect of PA on inhibition showed a moderate beneficial effect, but this was not statistically significant. The direction of the beneficial effect is however in line with the findings of the systematic review by Alvarez-Bueno et al. (2017), that found a positive effect for PA on inhibition in neurotypically developing children, and Cerrillo-Urbina et al. (2015) who conducted a meta-analysis on the effects of PA on ADHD symptoms finding a statistically significant medium effect in impulsivity scores. Deviating results in the present study may be explained by the outlying results of Rezaei et al.(2019), which indicated an inferior effect for PA on inhibition compared to no treatment. Rezaei et al.'s (2019) negative results may be explained by the nature of the yoga intervention employed with a focus on meditation, relaxation, deep breathing and mental imagination, and thus lacking contextual interference demands necessary to enhance inhibition (Best, 2010). Indeed, the sensitivity analysis (stated in protocol) excluding Rezaei et al. (2019) from the meta-analysis, resulted in a statistically significant large overall effect and a 95%-*CI* compatible with positive effect sizes on inhibition measures. Removing Rezaei et al. (2019) from the meta-analysis does not allow definitive interpretation, but raises a new hypothesis that benefits of PA on inhibition may depend on the nature of the PA. The deviating impact of Rezaei et al. (2019) could further be explained by the small sample size ($n = 7$ per group) counteracted by low weighting in the meta-analysis, the differing outcome measure compared to other primary studies included and unclear risks for several biases.

Shifting. This domain showed the greatest overall effect in this review, though the large 95%-*CI* indicates low precision and needs attention while interpreting the results. Although this finding is based on only three studies (Benzing & Schmidt, 2019; Da Silva et al., 2019; Pan et al., 2019), it is an encouraging finding and offers a promising avenue for further research. Alvarez-Bueno et al. (2017) also included this domain in their meta-analysis on children without ADHD and found a small but statistically non-significant effect ($N = 5$). A potential explanation for the different findings is that in the domain of shifting, children with ADHD benefit more from PA interventions than neurotypically developing children. This is consistent with Drollette et al.'s (2014) finding that those with greater deficits tend to benefit most from acute PA bouts.

Working Memory. From three studies included for this domain there was evidence of a large beneficial effect of PA on working memory, albeit smaller compared to other domains. This finding is consistent with review evidence in children with (Suarez-Manzano et al., 2018) and without ADHD (Álvarez-Bueno et al., 2017).The smaller effects on working memory compared to the other processes analyzed in this review may be due to the contextual interference of PA interventions. Contextual interference results in cognitive and coordinative demands, which appear to improve inhibition in particular but may not be as easily transferable to processes of the working memory (Álvarez-Bueno et al., 2017). While interpreting the results within the meta-analysis one has to keep in mind that for one of only three studies (Ziereis & Jansen, 2015), scores of the experimental group were compared to only one control group which was split in half for the analysis to avoid unit-of-analysis error (Higgins & Thompson, 2002).

Attention. The overall large effect of PA on attention was beneficial but statistically non-significant and with a wide confidence interval. However, results are based on only two primary studies. Results are in line with the reviews by Cerrillo-Urbina et al. (2015), De Greef et al. (2017) and Suarez-Manzano et al. (2018), for both children with and without ADHD. Though both studies in the current review included samples treated with MPH, their results differed in the effect of PA on attention. Results by Verret et al. (2012) may be influenced by the greater number of children taking MPH in the control group (11 of 11) compared to those in the experimental group (3 of 10). Contrary to this, Chou & Huang (2017) had balanced MPH-intake in both groups. The sample size of Chou & Huang (2017) was also larger than in other primary studies included, increasing the sensitivity to effects in the population. Lastly, they used yoga sessions specifically focusing on concentration and attention rather than other EF domains possibly explaining the superior effect of their lower-cognitively demanding PA compared to enriched PA as with the aerobic ball game exercises used by Verret et al. (2012).

Moderator analyses

Cognitive demand and MPH-intake were investigated in the moderator analyses to gain a better understanding of the underlying mechanisms with which PA affects EFs in children with ADHD. With the multi-causal etiology of ADHD including genetic and environmental causes and their interaction resulting in neurobiological differences (Brock et al., 2009a), different pathways via which PA influences cognitive functions need to be considered.

We considered that high cognitively demanding PA may activate multiple pathways simultaneously, and thus have greater impact for children with ADHD (Best, 2010). The findings of the moderator analyses indicated a greater beneficial effect for more cognitively demanding PA interventions on inhibition. These PA activities included table tennis and Tae-kwon-do both with specific coordinative and cognitive demands assumed to specifically benefit inhibition (Álvarez-Bueno et al., 2017). Additionally, superior effects found in this domain in the present participants are in line with Barkley´s model (1997) for ADHD assuming inhibition to be the essential deficit. This is supported by the findings of Drollette et al. (2014).

Findings are further in line with the hypo-arousal model highlighting decreased neural activity to be underlying the deficits in children with ADHD (Pontifex, Saliba, Raine, Picchietti, & Hillman, 2013). This is counteracted by PA by increasing the co-activity of the PFC, cerebellum and basal ganglia, all cerebral structures associated with ADHD (Chaddock et al., 2010; Pontifex et al., 2013; Suarez-Manzano et al., 2018; van der Fels et al., 2015). PA generally requires EFs (Best, 2010), which are allocated to the lateral PFC (Invernizzi et al., 2018). The PFC is also activated while learning new things (Diamond, 2013). More enriched PA interventions thus result in greater cognitive engagement required to execute complex motor movements leading to greater effects.

Contrary to the expected effect, PA higher in cognitive demand showed an inferior effect for working memory, shifting and attention than low cognitively demanding PA. Subgroup differences were statistically significant only for shifting and attention. A possible explanation for these findings may be that the PA led to cognitive overload. Children with ADHD struggle with motor skills, and therefore require higher executive control to precisely perform the required movements compared to neurotypically developing children (Pesce et al., 2013). As for the domain shifting, swimming as a low cognitively demanding intervention (Da Silva et al., 2019) demonstrated greater effect than the more cognitively demanding activities of table tennis (Pan et al., 2019) and exergaming (Benzing & Schmidt, 2019). This finding is surprising, especially as one would assume PA high in contextual interference to be specifically beneficial for shifting as the constantly changing demands would trigger cognitive flexibility. The requirements of PA such as exergaming and table tennis may have crossed the threshold of the optimal challenge point, indicating the degree of difficulty a functional task should have to optimize learning of a specific skill (Benzing & Schmidt, 2019; Pan et al., 2019).

Alternatively, it is possible that different intensities of these activities influenced the effects of the interventions. Tomporowski (2003) proposes an inverted U-shaped relationship between PA intensity and EF, with MVPA resulting in the greatest benefits. In the study by Benzing & Schmidt (2019) participants were only supervised in the first exergaming session while all following sessions were not monitored, so intensity of the PA may be questionable. Pan et al. (2019) and Da Silva et al. (2019) did not monitor intensity however participants might have reached a level of MVPA. This may explain the greater ES in the latter despite a low-cognitively demanding PA as intervention. Participants in this study were also on average older and therefore more likely to master the shifting on a trial-by-trial basis better which is required by the standard task-switching paradigms (Davidson, Amso, Anderson, & Diamond, 2006).

Results by Benzing & Schmidt (2019) may have also been influenced by the lack of social interaction, as their exergaming intervention was the only one set at home in an isolated setting compared to interventions conducted in groups used by the other included studies. Social interaction is assumed to be another pathway by which PA enhances EF, buffering the stress of exercising (Best, 2010). This is supported by the findings of rats benefitting from exercise only when housed together rather than when isolated (Stranahan, Khalil, & Gould, 2006). For attention, yoga focusing on meditation, breathing and relaxation led to the greatest effect size, and is in line with Hölzel et al. (2011) who reported meditation that reduces mind-wandering may subsequently improve attention. There is clearly a need for further research to which considers the influence of PA on the differing domains, and to unpick the influence of cognitive demand.

Analysis of the moderating effect of MPH-intake was only applicable for the domains inhibition and working memory. For working memory, the effect was slightly larger in participants with MPH-intake, however showed a wide 95%-*CI* including both positive and negative ES. In relation to inhibition, the effect was greater in the subgroup of MPH-free participants, potentially indicating MPH has a stronger effect and masks the one evoked by PA. This is in line with the the notion of PA interventions to be inferior to treatment with MPH (Janssen et al., 2016). This assumption is congruent with the suggestion of PA as adjunctive rather than isolated treatment for children with ADHD (Hoza, Martin, Pirog, & Shoulberg, 2016; Kang et al., 2011). However, further studies are necessary to consider establishing PA as single treatment option.

Strengths and Limitations

This study was designed to update and build on prior systematic literature reviews, while focusing on the effect of chronic PA on EF for children with ADHD specifically. EF is not a unitary construct and it is misleading to combine different aspects to give one overall ES. Thus, a strength of this study is its novelty being the first meta-analyses examining the effect of PA on separate domains of EF for children with ADHD increasing the precision of former results. Further, moderator analyses were included regarding cognitive demand and MPH-intake. Rigorous methods were implemented by following the Cochrane Guidelines for Systematic Reviews, a published study protocol, and two researchers involved in the screening process.

Nevertheless, there are some limitations that should be recognized when interpreting the findings. Due to our decision to focus the analysis on specific ES according to outcomes from every study, the full range of outcomes from primary studies have been excluded from the analyses. Future meta-analyses could consider using hierarchical modeling (Cheung, 2019), which would allow the inclusion of all outcomes as it allows the analysis of nested variables. This approach may also address the wide 95%-*CI* which have been reported throughout this current review. Although SMD is a recognized method of calculating effect sizes, this can lead to overestimations of the real effect. Hedge's adjusted *g*, which includes a pooled standard deviation in the denominator and can be corrected for error, could be a better option for further meta-analysis of studies investigating clinical populations that often have small sample sizes (Hartung, Knapp, & Sinha, 2008). Further, some studies were at risk for bias by not meeting the randomization quality criteria and reporting incomplete or selective outcomes. The risk of selection bias remained unclear in most studies included. Due to the few studies eligible for the review, those with high or unclear risk for bias were included in the analysis which needs to be considered when interpreting the results. Fourthly, generalizability of the results is limited as included studies showed high heterogeneity due to differing outcome measures and intervention characteristics across all meta-analyses and unequal gender distribution, which is to be expected given the higher prevalence of diagnosed ADHD in males (Wittchen & Hoyer, 2011). Additionally, only few primary studies met inclusion criteria resulting in a small number of studies included in the various meta-analysis, especially regarding the moderator analysis.

Lastly, PA levels, age, gender, socio-economic status (SES) and parental education level of the participants were not included as possible covariates. Finally, heterogeneity is considered substantial across the meta-analyses conducted in this review as indicated by the I^2, thus limiting the generalizability of the results due to various factors mentioned above. The aim of this review however is to map the existing evidence and identify a range of PA interventions and measures of EF.

Future research

As in prior studies the current review shows the beneficial effect of PA regarding symptoms of ADHD in children, and thus supports PA as adjunctive treatment. Further research however is necessary to confirm PA as single treatment option. For this, studies should investigate the efficacy of PA in participants without MPH to reveal the unmasked effect of PA before taking a further step of comparing PA to other treatment measures to establish PA as single treatment option.

The findings of this review also indicate that the cognitive demand of the PA may have varying effects on different domains of EF. Further research is required to explore this preliminary finding to get a better understanding how PA should be structured to best address the varying cognitive processes separately or simultaneously. Further, different types of PA should be considered in future analyses. This may include moderator analyses of aerobic vs. anaerobic, or coordinative vs. endurance tailored PA interventions. Another moderator worthy of consideration in future reviews is the degree of social interaction during PA sessions.

Future studies should further include PA levels of all participants, SES and parent education level and consider these when assessing the effect of PA interventions to control for possible confounding effects. Further covariates such as age and gender should be controlled for. To reduce the risk of bias, future research should aim to incorporate randomization and allocation concealment from investigators.

Conclusion

The review aimed to investigate the effect of PA on EFs in children with ADHD. Results showed mixed findings for separate processes of EF, but nevertheless favoured PA interventions overall compared to no treatment. The effect of cognitive demand depended on the EF processes measured and should be considered when implementing PA as treatment, whilst the effect of PA appeared to be independent of MPH treatment status. Future research is necessary to strengthen the scientific evidence and to increase generalizability and reliability of the findings to determine the effectiveness of PA as single treatment for children with ADHD. Supported by the current findings and the assumption of EF underlying ADHD symptoms, PA is suggested as adjunctive therapy to traditional treatments for ADHD.

References

Ahmed, G., & Mohamed, S. (2011). Effect of regular aerobic exercise on behavioural, cognitive and psychological response in patients with Attention-Deficit/Hyperactivity Disorder. *Life Science Journal*, *8*(2), 366–371.

Álvarez-Bueno, C., Pesce, C., Cavero-Redondo, I., Sánchez-López, M., Martínez-Hortelano, J. A., & Martínez-Vizcaíno, V. (2017). The effect of physical activity interventions on children`s cognition and metacognition: A systematic review and meta-analysis. *Journal of the American Academy of Child & Adolescent Psychiatry*, *56*(9), 729–738.

American Psychiatric Association. (2013). *Diagnostic and Statistical Manual of Mental Disorders: DSM-5*. *American Psychiatric Association* (5th ed.). Arlington, VA.: American Psychiatric Association.

Baddeley, A., & Hitch, G. (1974). *Working Memory*. (G. H. Bower, Ed.) (8th ed.). New York: Academic Press Inc.

Bailey, R. (2006). Physical education and sport in schools: A review of benefits and outcomes. *Journal of School Health*, *76*(8), 397–401.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*(1), 65–94.

Barnard-Brak, L., Davis, T., Sulak, T., & Brak, V. (2011). The association between physical education and symptoms of attention deficit hyperactivity disorder. *Journal of Physical Activity & Health*, *8*(7), 964–970.

Benzing, V., & Schmidt, M. (2019). The Effect of Exergaming on Executive Functions in Children with ADHD : A Randomized Clinical Trial. *Scandinavian Journal of Medicine & Science in Sports*, (November 2018), 1–11.

Best, J. R. (2010). Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Developmental Review*, *30*(4), 331–351.

Brady, F. (2008). The contextual interference effect and sport skills. *Perceptual and Motor Skills*, *106*(2), 461–472.

Brock, S. E., Jimerson, S. R., & Hansen, R. L. (2009a). Causes. In *Identifying, Assessing, and Treating ADHD at School* (pp. 9–20). Boston, MA: Springer.

Brock, S. E., Jimerson, S. R., & Hansen, R. L. (2009b). *Identifying, assessing, and treating ADHD at school*.

Cerrillo-Urbina, A. J., García-Hermoso, A., Sánchez-López, M., Pardo-Guijarro, M. J., Santos Gómez, J. L., & Martínez-Vizcaíno, V. (2015). The effects of physical exercise in children with attention deficit hyperactivity disorder: A systematic review and meta-analysis of randomized control trials. *Child: Care, Health and Development*, *41*(6), 779–788.

Chaddock, L., Erickson, K. I., Prakash, R. S., Kim, J. S., Voss, M. W., VanPatter, M., … Kramer, A. F. (2010). A neuroimaging investigation of the association between aerobic fitness, hippocampal volume, and memory performance in preadolescent children. *Brain*

Research, *1358*, 172–183.

Chang, Y.-K., Hung, C.-L., Huang, C.-J., Hatfield, B. D., & Hung, T.-M. (2014). Effects of an aquatic exercise program on inhibitory control in children with ADHD: A preliminary study. *Archives of Clinical Neuropsychology*, *29*(3), 217–223.

Cheung, M. W. (2019). A Guide to Conducting a Meta-Analysis with Non-Independent Effect Sizes. *Neuropsychology Review*, *29*, 387–396.

Chou, C.-C., & Huang, C.-J. (2017). Effects of an 8-week yoga program on sustained attention and discrimination function in children with attention deficit hyperactivity disorder. *PeerJ*, *5*(e2883), 1–17.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawerenec Erlbaum Associates, Inc.

Cornelius, C., Fedewa, A. L., & Ahn, S. (2017). The effect of physical activity on children with ADHD: A quantitative review of the literature. *Journal of Applied School Psychology*, *33*(2), 136–170.

Cumming, G. (2012). *Understanding the new statistics: Effect sizes, confidence intervals, and meta-analysis* (1st ed.). New York: Routledge.

Da Silva, L. A., Doyenart, R., Henrique Salvan, P., Rodrigues, W., Felipe Lopes, J., Gomes, K., … Silveira, P. C. (2019). Swimming training improves mental health parameters, cognition and motor coordination in children with Attention Deficit Hyperactivity Disorder. *International Journal of Environmental Health Research*, *00*(00), 1–9.

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*(11), 2037–2078.

De Greeff, J. W., Bosker, R. J., Oosterlaan, J., Visscher, C., & Hartman, E. (2017). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: a meta-analysis. *Journal of Science and Medicine in Sport*, *21*(5), 501–507.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development*, *71*(1), 44–56.

Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, *64*, 135–168.

Drollette, E. S., Scudder, M. R., Raine, L. B., Moore, R. D., Saliba, B. J., Pontifex, M. B., & Hillman, C. H. (2014). Acute exercise facilitates brain function and cognition in children who need it most: An ERP study of individual differences in inhibitory control capacity. *Developmental Cognitive Neuroscience*, *7*, 53–64.

Hartung, J., Knapp, G., & Sinha, B. K. (2008). *Statistical Meta-Analysis with Applications*. (D. J. Balding, N. A. C. Cressie, G. M. Fitzmaurice, I. M. Johnstone, G. Molenberghs, D. W. Scott, … S. Weisberg, Eds.) (1st ed.). John Wiley & Sons, Inc.

Higgins, J. P. T., & Green, S. (2011). Cochrane Handbook for Systematic Reviews of Interventions. *Cochrane Handbook for Systematic Reviews of Interventions Version 5.1.0*.

Higgins, J. P. T., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine*, *21*(11), 1539–1558.

Hölzel, B. K., Lazar, S. W., Gard, T., Schuman-olivier, Z., Vago, D. R., & Ott, U. (2011). How Does Mindfulness Meditation Work? Proposing Mechanisms of Action From a Conceptual and Neural Perspective. *Perspecties on Psychological Science*, *6*(6), 537–559.

Hoza, B., Martin, C. P., Pirog, A., & Shoulberg, E. K. (2016). Using physical activity to manage ADHD symptoms: The state of the evidence. *Current Psychiatry Reports*, *18*(12).

IBM Corperation. (2015). IBM SPSS Statistics for Windows. Armonk: IBM Corperation.

Invernizzi, P. L., Crotti, M., Bosio, A., Scurati, R., & Lovecchio, N. (2018). Correlation between Cognitive Functions and Motor Coordination in Children with Different Cognitive Levels. *Advances in Physical Education*, *08*(01), 98–115.

Janssen, T. W. P., Bink, M., Geladé, K., van Mourik, R., Maras, A., & Oosterlaan, J. (2016). A Randomized Controlled Trial Investigating the Effects of Neurofeedback, Methylphenidate, and Physical Activity on Event-Related Potentials in Children with Attention-Deficit/Hyperactivity Disorder. *Journal of Child and Adolescent Psychopharmacology*, *26*(4), 344–353.

Kadri, A., Slimani, M., Bragazzi, N. L., Tod, D., & Azaiez, F. (2019). Effect of taekwondo practice on cognitive function in adolescents with attention deficit hyperactivity disorder. *International Journal of Environmental Research and Public Health*, *16*(2), 1–10.

Kang, K. D., Choi, J. W., Kang, S. G., & Han, D. H. (2011). Sports Therapy for Attention, Cognitions and Sociality. *International Journal of Sports Medicine*, *32*, 953–959.

Kiluk, B. D., Weden, S., & Culotta, V. P. (2009). Sport participation and anxiety in children with ADHD. *J Atten Disord*, *12*(6), 499–506.

Lee, S. K., Song, J., & Park, J. H. (2017). Effects of combination exercises on electroencephalography and frontal lobe executive function measures in children with ADHD: A pilot study. *Biomedical Research (India)*, (Special Issue Health Science and Bio Convergence Technology Edition-II), S455–S460.

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., … Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *BMJ (Clinical Research Ed.)*, *339*(b2700).

Memarmoghaddam, M., Torbati, H. T., Sohrabi, M., Mashhadi, A., & Kashi, A. (2016). Effects of a selected exercise program on executive function of children with attention deficit hyperactivity disorder. *Journal of Medicine and Life*, *9*(4), 373–379.

Molina, B. S. G., Hinshaw, S. P., Swanson, J. M., Arnold, L. E., Vitiello, B., Jensen, P., … MTA Cooperative Group. (2009). The MTA at 8 years: Prospective follow-up of children treated for combined type ADHD in a multisite study. *Journal of the American Academy of Child & Adolescent Psychiatry*, *48*(5), 484–500.

O'Neill, S. C., Berwid, O. G., & Bédard, A. C. V. (2016). The Exercise-Cognition Interaction and ADHD. In *Exercise-Cognition Interaction: Neuroscience Perspectives* (pp. 375–398).

Page, M. (2018). Introduction to RevMan - a guided tour. Retrieved from https://training.cochrane.org/resource/introduction-revman-—-guided-tour

Pan, C. Y., Chu, C. H., Tsai, C. L., Lo, S. Y., Cheng, Y. W., & Liu, Y. J. (2016). A racket-sport intervention improves behavioral and cognitive performance in children with attention-deficit/hyperactivity disorder. *Research in Developmental Disabilities*, *57*(116), 1–10.

Pan, C. Y., Tsai, C. L., Chu, C. H., Sung, M. C., Huang, C. Y., & Ma, W. Y. (2019). Effects of Physical Exercise Intervention on Motor Skills and Executive Functions in Children With ADHD: A Pilot Study. *Journal of Attention Disorders*, *23*(4), 384–397.

Pesce, C., Crova, C., Marchetti, R., Struzzolino, I., Masci, I., Vannozzi, G., & Forte, R. (2013). Searching for cognitively optimal challenge point in physical activity for children with typical and atypical motor development. *Mental Health and Physical*

Activity, *6*(3), 172–180.

Pontifex, M. B., Saliba, B. J., Raine, L. B., Picchietti, D. L., & Hillman, C. H. (2013). Exercise improves behavioral, neurocognitive, and scholastic performance in children with attention-deficit/hyperactivity disorder. *Journal of Pediatrics*, *162*(3), 543–551.

Rezaei, M., Salarpor Kamarzard, T., & Najafian Razavi, M. (2019). The Effects of Neurofeedback, Yoga Interventions on Memory and Cognitive Activity in Children with Attention Deficit/Hyperactivity Disorder: A Randomized Controlled Trial. *Annals of Applied Sport Science*, *6*(4), 17–27.

Smith, B. H., & Shapiro, C. J. (2015). Combined treatments for ADHD. In R. A. Barkley (Ed.), *Attention-deficit/hyperactivity disorder: A handbook for diagnosis and treatment* (4th ed., pp. 686–704). New York: The Guilford Press.

Smith, M. (2013). *Hyperactive: The Controversial History of ADHD. British Library Cataloguing* (Vol. 33).

Stranahan, A. M., Khalil, D., & Gould, E. (2006). Social isolation delays the positiv effects of running on adult neurogenesis. *Nature Neuroscience*, *9*(4), 526–533.

Suarez-Manzano, S., Ruiz-Ariza, A., De La Torre-Cruz, M., & Martínez-López, E. J. (2018). Acute and chronic effect of physical activity on cognition and behaviour in young people with ADHD: A systematic review of intervention studies. *Research in Developmental Disabilities*, *77*(March), 12–23.

Tantillo, M., Kesick, C. M., Hynd, G. W., & Dishman, R. K. O. D. K. (2002). The effects of exercise on children with attention-deficit hyperactivity disorder. *Medicine and Science in Sports and Exercise*, *34*(2), 203–212.

The Nordic Cochrane Centre. (2014). Review Manager. Copenhagen: The Cochrane Collaboration.

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychologica*, *112*(3), 297–324.

van der Fels, I. M. J., te Wierike, S. C. M., Hartman, E., Elferink-Gemser, M. T., Smith, J., & Visscher, C. (2015). The relationship between motor skills and cognitive skills in 4-16 year old typically developing children: A systematic review. *Journal of Science and Medicine in Sport*, *18*(6), 697–703.

Verburgh, L., Königs, M., Scherder, E. J. A., & Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: a meta-analysis. *British Journal of Sports Medicine*, *48*(12), 973–979.

Verret, C., Guay, M.-C., Berthiaume, C., Gardiner, P., & Béliveau, L. (2012). A physical activity program improves behavior and cognitive functions in children with ADHD. *Journal of Attention Disorders*, *16*(1), 71–80.

Vysniauske, R., Verburgh, L., Oosterlaan, J., & Molendijk, M. L. (2016). The effects of physical exercise on functional outcomes in the treatment of ADHD: A meta-analysis. *Journal of Attention Disorders*.

Welsch, L., Alliott, O., Fawkner, S., & Niven, A. (2018). The effect of long-term physical activity intervention on executive functions in children with ADHD: A systematic review and meta-analysis. *PROSPERO*.

Wittchen, H.-U., & Hoyer, J. (Eds.). (2011). *Klinische Psychologie & Psychotherapie* (2nd ed.). Heidelberg: Springer.

Ziereis, S., & Jansen, P. (2015). Effects of physical activity on executive function and motor performance in children with ADHD. *Research in Developmental Disabilities*, *38*, 181–191.

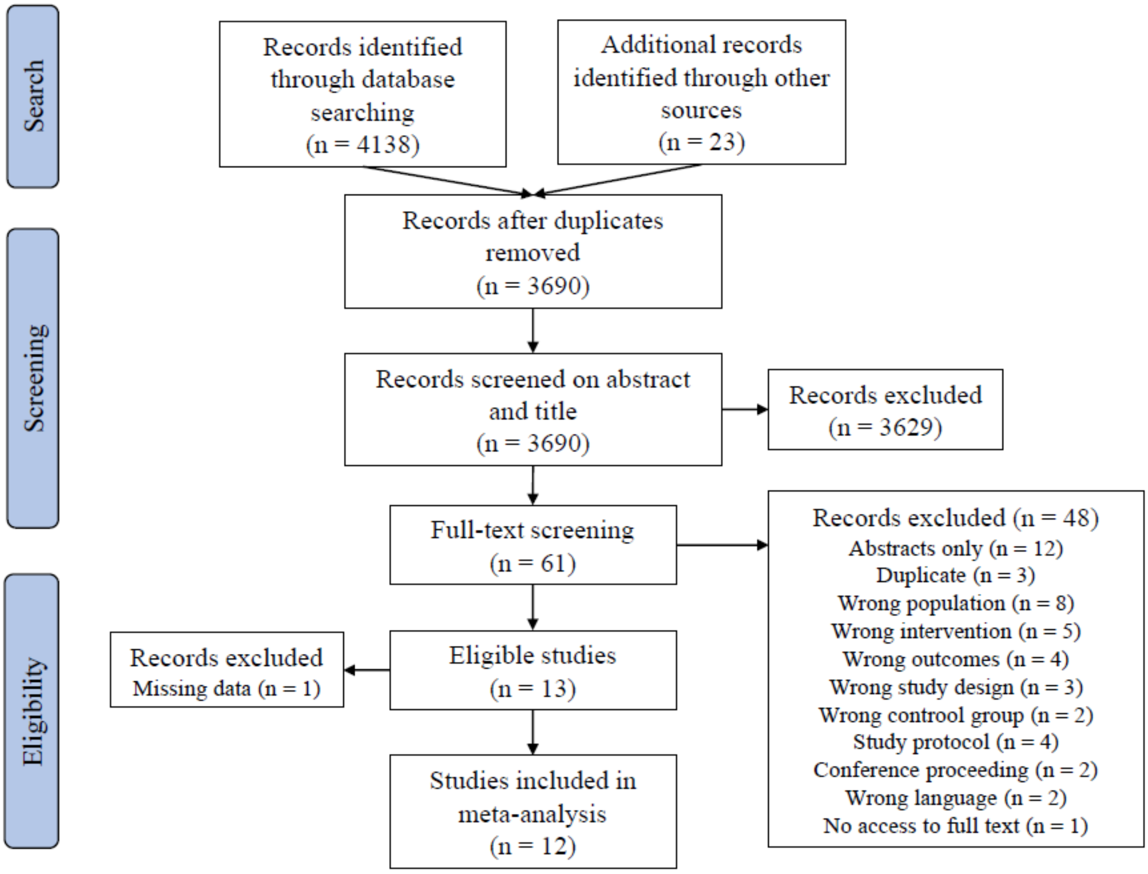
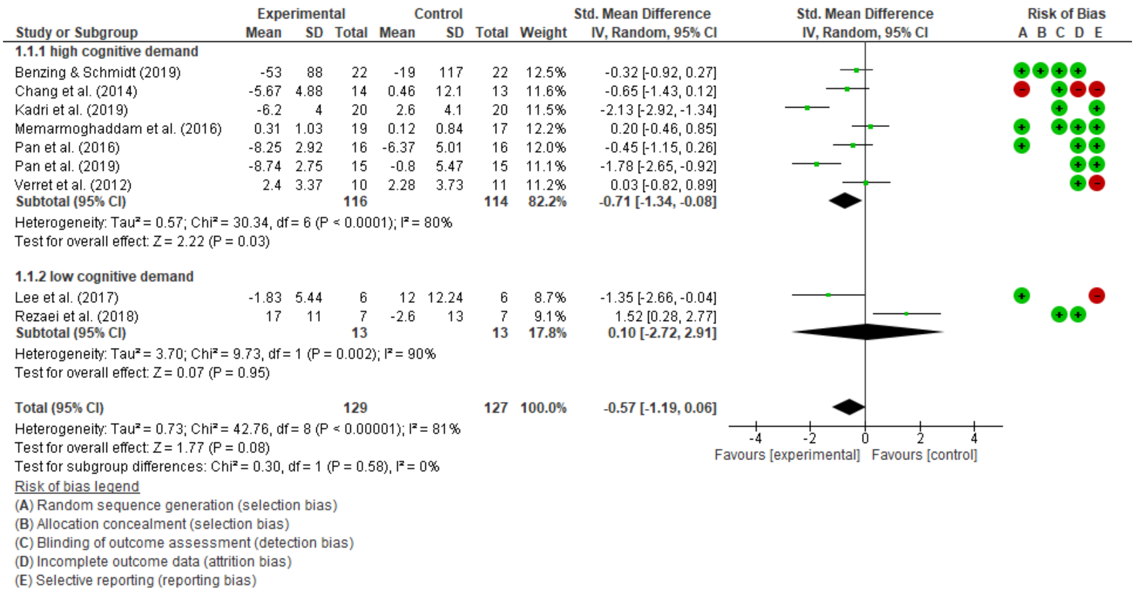


Figure 1. PRISMA flow diagram of the selection process of eligible studies.

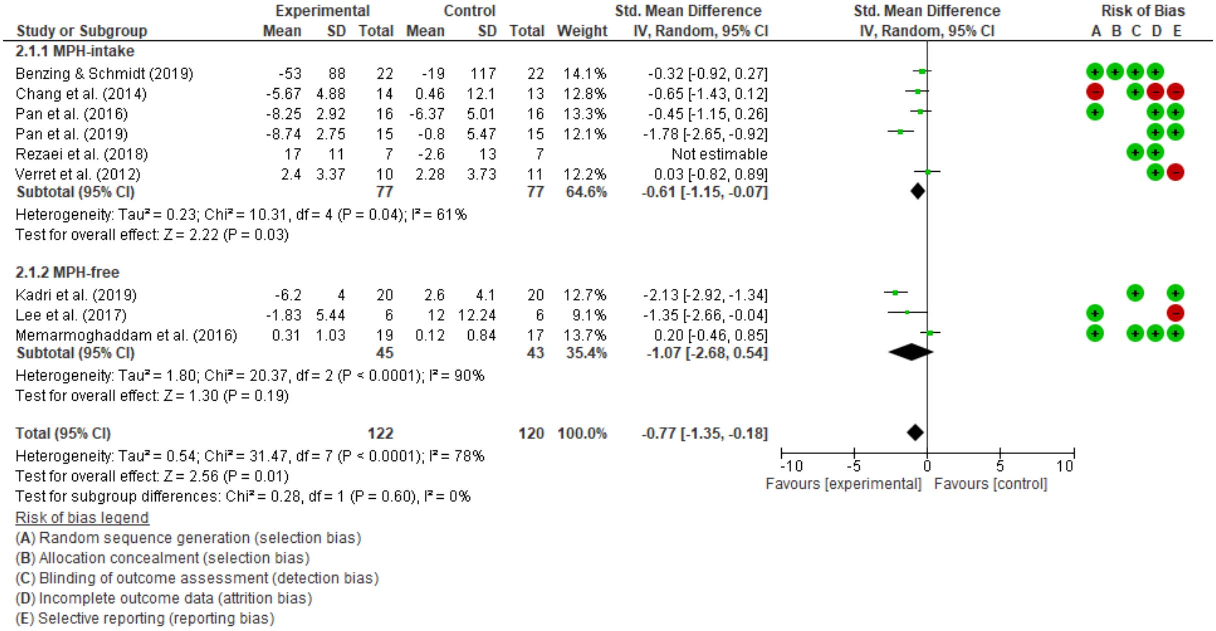


Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI	Risk of Bias A	B	C	D	E
1.1.1 high cognitive demand													
Benzing & Schmidt (2019)	-53	88	22	-19	117	22	12.5%	-0.32 [-0.92, 0.27]	+	+	+	+	
Chang et al. (2014)	-5.67	4.88	14	0.46	12.1	13	11.6%	-0.65 [-1.43, 0.12]	−		+	−	−
Kadri et al. (2019)	-6.2	4	20	2.6	4.1	20	11.5%	-2.13 [-2.92, -1.34]			+		+
Memarmoghaddam et al. (2016)	0.31	1.03	19	0.12	0.84	17	12.2%	0.20 [-0.46, 0.85]	+		+	+	+
Pan et al. (2016)	-8.25	2.92	16	-6.37	5.01	16	12.0%	-0.45 [-1.15, 0.26]	+			+	+
Pan et al. (2019)	-8.74	2.75	15	-0.8	5.47	15	11.1%	-1.78 [-2.65, -0.92]				+	+
Verret et al. (2012)	2.4	3.37	10	2.28	3.73	11	11.2%	0.03 [-0.82, 0.89]				+	−
Subtotal (95% CI)			**116**			**114**	**82.2%**	**-0.71 [-1.34, -0.08]**					
Heterogeneity: Tau² = 0.57; Chi² = 30.34, df = 6 (P < 0.0001); I² = 80%													
Test for overall effect: Z = 2.22 (P = 0.03)													
1.1.2 low cognitive demand													
Lee et al. (2017)	-1.83	5.44	6	12	12.24	6	8.7%	-1.35 [-2.66, -0.04]	+				−
Rezaei et al. (2018)	17	11	7	-2.6	13	7	9.1%	1.52 [0.28, 2.77]			+	+	
Subtotal (95% CI)			**13**			**13**	**17.8%**	**0.10 [-2.72, 2.91]**					
Heterogeneity: Tau² = 3.70; Chi² = 9.73, df = 1 (P = 0.002); I² = 90%													
Test for overall effect: Z = 0.07 (P = 0.95)													
Total (95% CI)			**129**			**127**	**100.0%**	**-0.57 [-1.19, 0.06]**					

Heterogeneity: Tau² = 0.73; Chi² = 42.76, df = 8 (P < 0.00001); I² = 81%
Test for overall effect: Z = 1.77 (P = 0.08)
Test for subgroup differences: Chi² = 0.30, df = 1 (P = 0.58), I² = 0%

Risk of bias legend
(**A**) Random sequence generation (selection bias)
(**B**) Allocation concealment (selection bias)
(**C**) Blinding of outcome assessment (detection bias)
(**D**) Incomplete outcome data (attrition bias)
(**E**) Selective reporting (reporting bias)

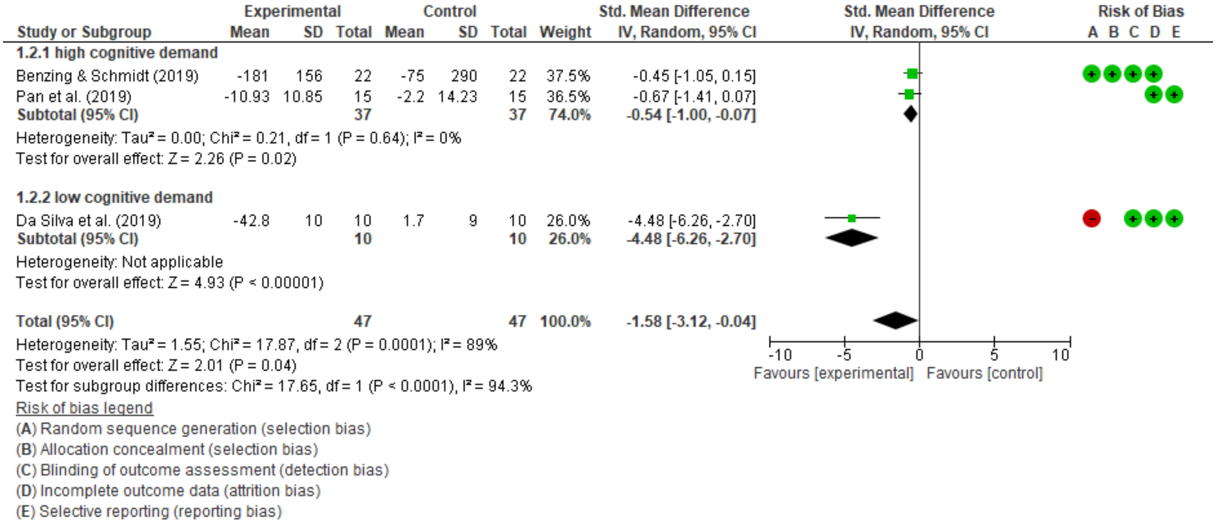
Figure 2. Forrest plot of the effect of physical activity interventions on inhibition including moderator analysis for cognitive demand.



	Experimental			Control				Std. Mean Difference	Risk of Bias				
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Random, 95% CI**	**A**	**B**	**C**	**D**	**E**
2.1.1 MPH-intake													
Benzing & Schmidt (2019)	-53	88	22	-19	117	22	14.1%	-0.32 [-0.92, 0.27]	+	+	+	+	
Chang et al. (2014)	-5.67	4.88	14	0.46	12.1	13	12.8%	-0.65 [-1.43, 0.12]	−		+	−	−
Pan et al. (2016)	-8.25	2.92	16	-6.37	5.01	16	13.3%	-0.45 [-1.15, 0.26]	+			+	+
Pan et al. (2019)	-8.74	2.75	15	-0.8	5.47	15	12.1%	-1.78 [-2.65, -0.92]				+	+
Rezaei et al. (2018)	17	11	7	-2.6	13	7		Not estimable			+	+	
Verret et al. (2012)	2.4	3.37	10	2.28	3.73	11	12.2%	0.03 [-0.82, 0.89]				+	−
Subtotal (95% CI)			**77**			**77**	**64.6%**	**-0.61 [-1.15, -0.07]**					
Heterogeneity: Tau² = 0.23; Chi² = 10.31, df = 4 (P = 0.04); I² = 61%													
Test for overall effect: Z = 2.22 (P = 0.03)													
2.1.2 MPH-free													
Kadri et al. (2019)	-6.2	4	20	2.6	4.1	20	12.7%	-2.13 [-2.92, -1.34]			+		+
Lee et al. (2017)	-1.83	5.44	6	12	12.24	6	9.1%	-1.35 [-2.66, -0.04]	+				−
Memarmoghaddam et al. (2016)	0.31	1.03	19	0.12	0.84	17	13.7%	0.20 [-0.46, 0.85]	+		+	+	+
Subtotal (95% CI)			**45**			**43**	**35.4%**	**-1.07 [-2.68, 0.54]**					
Heterogeneity: Tau² = 1.80; Chi² = 20.37, df = 2 (P < 0.0001); I² = 90%													
Test for overall effect: Z = 1.30 (P = 0.19)													
Total (95% CI)			**122**			**120**	**100.0%**	**-0.77 [-1.35, -0.18]**					
Heterogeneity: Tau² = 0.54; Chi² = 31.47, df = 7 (P < 0.0001); I² = 78%													
Test for overall effect: Z = 2.56 (P = 0.01)													
Test for subgroup differences: Chi² = 0.28, df = 1 (P = 0.60), I² = 0%													

Risk of bias legend
(**A**) Random sequence generation (selection bias)
(**B**) Allocation concealment (selection bias)
(**C**) Blinding of outcome assessment (detection bias)
(**D**) Incomplete outcome data (attrition bias)
(**E**) Selective reporting (reporting bias)

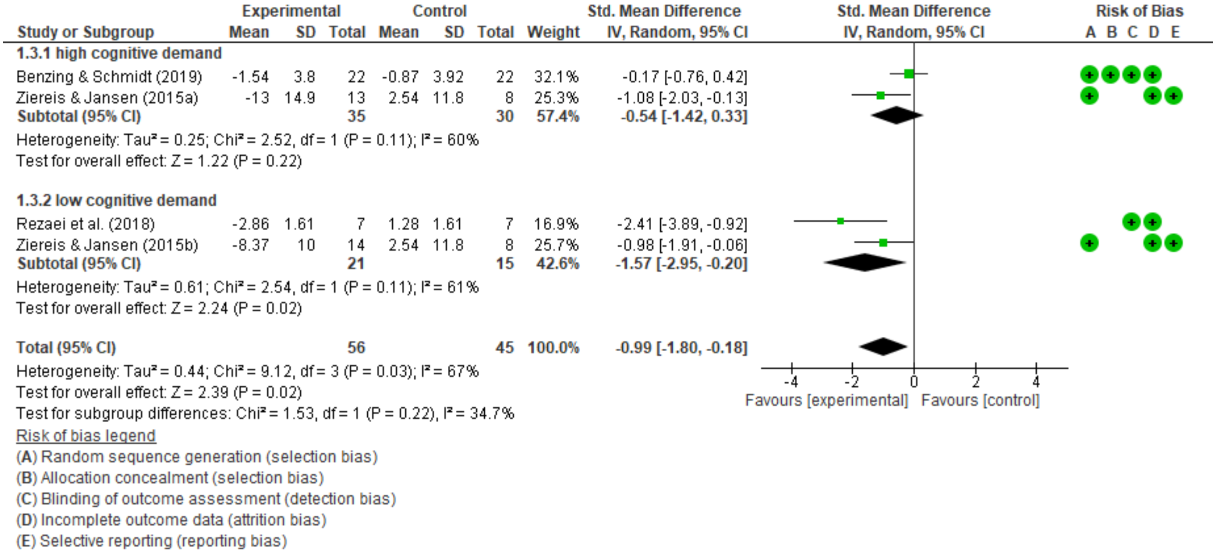
Figure 3. Forrest plot of the effect of physical activity interventions on inhibition excluding Rezaei et al. (2018) including moderator analysis for MPH intake.



	Experimental			Control				Std. Mean Difference	Risk of Bias				
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Random, 95% CI**	**A**	**B**	**C**	**D**	**E**
1.2.1 high cognitive demand													
Benzing & Schmidt (2019)	-181	156	22	-75	290	22	37.5%	-0.45 [-1.05, 0.15]	+	+	+	+	
Pan et al. (2019)	-10.93	10.85	15	-2.2	14.23	15	36.5%	-0.67 [-1.41, 0.07]				+	+
Subtotal (95% CI)			**37**			**37**	**74.0%**	**-0.54 [-1.00, -0.07]**					
Heterogeneity: Tau² = 0.00; Chi² = 0.21, df = 1 (P = 0.64); I² = 0%													
Test for overall effect: Z = 2.26 (P = 0.02)													
1.2.2 low cognitive demand													
Da Silva et al. (2019)	-42.8	10	10	1.7	9	10	26.0%	-4.48 [-6.26, -2.70]	−		+	+	+
Subtotal (95% CI)			**10**			**10**	**26.0%**	**-4.48 [-6.26, -2.70]**					
Heterogeneity: Not applicable													
Test for overall effect: Z = 4.93 (P < 0.00001)													
Total (95% CI)			**47**			**47**	**100.0%**	**-1.58 [-3.12, -0.04]**					
Heterogeneity: Tau² = 1.55; Chi² = 17.87, df = 2 (P = 0.0001); I² = 89%													
Test for overall effect: Z = 2.01 (P = 0.04)													
Test for subgroup differences: Chi² = 17.65, df = 1 (P < 0.0001), I² = 94.3%													

Risk of bias legend
(**A**) Random sequence generation (selection bias)
(**B**) Allocation concealment (selection bias)
(**C**) Blinding of outcome assessment (detection bias)
(**D**) Incomplete outcome data (attrition bias)
(**E**) Selective reporting (reporting bias)

Figure 4. Forrest plot of the effect of physical activity interventions on shifting including moderator analysis for cognitive demand.



Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI	A	B	C	D	E
1.3.1 high cognitive demand													
Benzing & Schmidt (2019)	-1.54	3.8	22	-0.87	3.92	22	32.1%	-0.17 [-0.76, 0.42]	+	+	+	+	
Ziereis & Jansen (2015a)	-13	14.9	13	2.54	11.8	8	25.3%	-1.08 [-2.03, -0.13]	+			+	+
Subtotal (95% CI)			**35**			**30**	**57.4%**	**-0.54 [-1.42, 0.33]**					
1.3.2 low cognitive demand													
Rezaei et al. (2018)	-2.86	1.61	7	1.28	1.61	7	16.9%	-2.41 [-3.89, -0.92]			+	+	
Ziereis & Jansen (2015b)	-8.37	10	14	2.54	11.8	8	25.7%	-0.98 [-1.91, -0.06]	+			+	+
Subtotal (95% CI)			**21**			**15**	**42.6%**	**-1.57 [-2.95, -0.20]**					
Total (95% CI)			**56**			**45**	**100.0%**	**-0.99 [-1.80, -0.18]**					

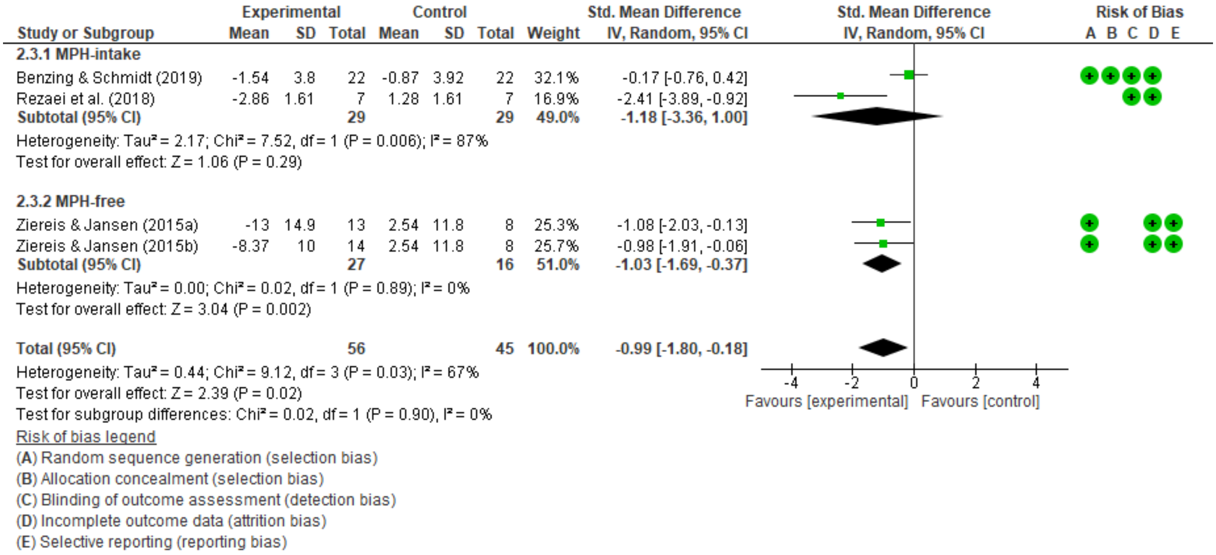
1.3.1 high cognitive demand:
Heterogeneity: Tau² = 0.25; Chi² = 2.52, df = 1 (P = 0.11); I² = 60%
Test for overall effect: Z = 1.22 (P = 0.22)

1.3.2 low cognitive demand:
Heterogeneity: Tau² = 0.61; Chi² = 2.54, df = 1 (P = 0.11); I² = 61%
Test for overall effect: Z = 2.24 (P = 0.02)

Total (95% CI):
Heterogeneity: Tau² = 0.44; Chi² = 9.12, df = 3 (P = 0.03); I² = 67%
Test for overall effect: Z = 2.39 (P = 0.02)
Test for subgroup differences: Chi² = 1.53, df = 1 (P = 0.22), I² = 34.7%

Risk of bias legend
(A) Random sequence generation (selection bias)
(B) Allocation concealment (selection bias)
(C) Blinding of outcome assessment (detection bias)
(D) Incomplete outcome data (attrition bias)
(E) Selective reporting (reporting bias)

Figure 5. Forrest plot of the effect of physical activity interventions on working memory including moderator analysis for cognitive demand.



Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI	A	B	C	D	E
2.3.1 MPH-intake													
Benzing & Schmidt (2019)	-1.54	3.8	22	-0.87	3.92	22	32.1%	-0.17 [-0.76, 0.42]	+	+	+	+	
Rezaei et al. (2018)	-2.86	1.61	7	1.28	1.61	7	16.9%	-2.41 [-3.89, -0.92]			+	+	
Subtotal (95% CI)			**29**			**29**	**49.0%**	**-1.18 [-3.36, 1.00]**					
2.3.2 MPH-free													
Ziereis & Jansen (2015a)	-13	14.9	13	2.54	11.8	8	25.3%	-1.08 [-2.03, -0.13]	+			+	+
Ziereis & Jansen (2015b)	-8.37	10	14	2.54	11.8	8	25.7%	-0.98 [-1.91, -0.06]	+			+	+
Subtotal (95% CI)			**27**			**16**	**51.0%**	**-1.03 [-1.69, -0.37]**					
Total (95% CI)			**56**			**45**	**100.0%**	**-0.99 [-1.80, -0.18]**					

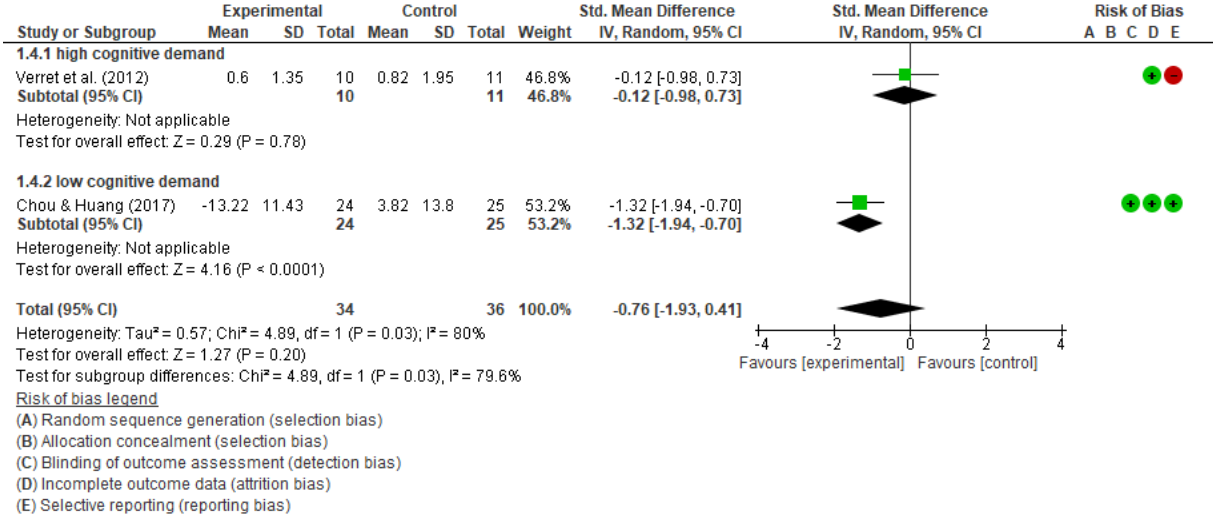
2.3.1 MPH-intake:
Heterogeneity: Tau² = 2.17; Chi² = 7.52, df = 1 (P = 0.006); I² = 87%
Test for overall effect: Z = 1.06 (P = 0.29)

2.3.2 MPH-free:
Heterogeneity: Tau² = 0.00; Chi² = 0.02, df = 1 (P = 0.89); I² = 0%
Test for overall effect: Z = 3.04 (P = 0.002)

Total (95% CI):
Heterogeneity: Tau² = 0.44; Chi² = 9.12, df = 3 (P = 0.03); I² = 67%
Test for overall effect: Z = 2.39 (P = 0.02)
Test for subgroup differences: Chi² = 0.02, df = 1 (P = 0.90), I² = 0%

Risk of bias legend
(A) Random sequence generation (selection bias)
(B) Allocation concealment (selection bias)
(C) Blinding of outcome assessment (detection bias)
(D) Incomplete outcome data (attrition bias)
(E) Selective reporting (reporting bias)

Figure 6. Forrest plot of the effect of physical activity interventions on working memory including moderator analysis for MPH-intake.



Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI	Risk of Bias A	B	C	D	E
1.4.1 high cognitive demand													
Verret et al. (2012)	0.6	1.35	10	0.82	1.95	11	46.8%	-0.12 [-0.98, 0.73]				+	−
Subtotal (95% CI)			**10**			**11**	**46.8%**	**-0.12 [-0.98, 0.73]**					
Heterogeneity: Not applicable													
Test for overall effect: Z = 0.29 (P = 0.78)													
1.4.2 low cognitive demand													
Chou & Huang (2017)	-13.22	11.43	24	3.82	13.8	25	53.2%	-1.32 [-1.94, -0.70]			+	+	+
Subtotal (95% CI)			**24**			**25**	**53.2%**	**-1.32 [-1.94, -0.70]**					
Heterogeneity: Not applicable													
Test for overall effect: Z = 4.16 (P < 0.0001)													
Total (95% CI)			**34**			**36**	**100.0%**	**-0.76 [-1.93, 0.41]**					

Heterogeneity: Tau² = 0.57; Chi² = 4.89, df = 1 (P = 0.03); I² = 80%
Test for overall effect: Z = 1.27 (P = 0.20)
Test for subgroup differences: Chi² = 4.89, df = 1 (P = 0.03), I² = 79.6%

Risk of bias legend
(A) Random sequence generation (selection bias)
(B) Allocation concealment (selection bias)
(C) Blinding of outcome assessment (detection bias)
(D) Incomplete outcome data (attrition bias)
(E) Selective reporting (reporting bias)

Figure 7. Forrest plot of the effect of physical activity interventions on attention including moderator analysis for cognitive demand.

Table 1

Systematic review search terms

Target population	Condition	Intervention	Outcome
Child*	ADHD	Exercis*	Cognitive function*
Adolescen*	ADD	Physical activity	Executive function*
Teenage*	Attention deficit/hyperactivity disorder	Aerobic exercise	Cogn*
Preadolescen*		Anaerobic exercise	Working memory
Primary school*		Physical Education	Inhibit*
Secondary school*	Attention deficit disorder	Sport*	Cognitive flexibility
School*		Fitness	Attention* control
Elementary school*			Executive control
Student*			
Pupil*			

**Word truncation; Search strategy combined the categories with "AND" and search terms within these categories with "OR".*

Table 2

Characteristics of the studies included in the meta-analysis

		Intervention Group			Control Group			PA intervention						
Primary study	diagnosis	n	mean age (SD)	MPH intake	n	mean age (SD)	MPH intake	PA	duration	type	cognitive demand	Intensity	control group	measures of EF **
Benzing & Schmidt (2018)	DSM-IV	22	10.46 (1.30)	7	22	10.39 (1.44)	17	exergaming	3x30 min.; 8 weeks	aerobic	yes	n.a.	Waiting list	Simon task; Colour span test Flanker Task
Chang et al. (2014)	DSM-IV-TR	14	8.19 (7.65)	7	13	8.78 (8.33)	6	swimming incl. perceptual-motor training	2x90 min.; 8 weeks	aerobic	yes	MPA (not monitored)	waiting list	Go-NoGo Task
Chou & Huang (2017)	n.a.	24	10.71 (1.00)	10	25	10.3 (1.00)	12	yoga	2x40 min.; 8 weeks	flexi-bility	no	MPA	none	DT
Da Silva et al. (2019)	DSM-IV	10	12.00 (2.00)	>1	10	12.00 (1.00)	>1	swimming	2x45 min.; 6weeks	aerobic	no	n.a.	none	TMT
Kadri et al. (2019)	n.a.	19	14.50 (3.50)	0	20	14.20 (3.00)		Taek-Won-Do	2x50 min.; 78 weeks	aerobic	yes	n.a.	none	Stroop Test***

CPT – Continuous Performance Test; DT - Discrimination Test; DST – Digit Span Task, HAWIK-IV - Hamburg-Wechsler-Intelligenztest für Kinder - IV; LNS – Letter-Number sequencing; MPA – moderate physical activity; MVPA – moderate to vigorous physical activity; MPH – Methylphenidate; n.a. – not recorded; TEA-C - Test of Everyday Attention for Children; TMT – Trail Making Task; WISC-R – Wechsler Intelligence Scale for Children – revised; * - *M* (age) of participants overall; ** - outcome measures included in this meta-analysis; *** - Interference Score; **** - Perseveration Error

		Intervention Group			Control Group			PA intervention						
Primary study	diagnosis	n	mean age (SD)	MPH intake	n	mean age (SD)	MPH intake	PA	duration	type	cognitive demand	Intensity	control group inter-vention	measures of EF**
Lee et al. (2017)	n.a.	6	8.83 (0.98)	0	6	8.83 (0.98)	0	combined exercises	2x60 min.; 12 weeks	aerobic	no	MVPA	none	Stroop Test***
Memarmoghaddam et al.	DSM-IV	19	8.31 (1.29)	0	17	8.29 (1.13)	0	aerobic exercises and ball games	3x90 min.; 8 weeks	aerobic	yes	MVPA	none	Stroop Test***
Pan et al. (2016)	DSM-IV	16	8.93 (1.49)	9	16	8.87 (1.56)	9	table tennis	2x70 min.; 12 weeks	aerobic	yes	n.a.	none	Stroop Test***
Pan et al. (2019)	DSM-IV	15	9.08 (1.43)	9	15	8.90 (1.66)	9	table tennis	2x70 min.; 12weeks	aerobic	yes	n.a.	none	Stroop Test*** WCST****
Rezaei et al. (2018)	DSM-V	7	n.a.	>1	7	n.a.	>1	Yoga	3x45 min; 8 weeks	flexibility	no	n.a.	none	CPT WISC-R (DST)
Verret et al. (2012)	DSM-IV	10	9.10* (1.10)	3	11	9.10* (1.10)	11	Aerobic exercise incl. Ball games	3x45 min.; 10 weeks	aerobic	yes	MVPA	none	TEA-C (score test & walk/ don`t walk)

CPT – Continuous Performance Test; DT - Discrimination Test; DST – Digit Span Task, HAWIK-IV - Hamburg-Wechsler-Intelligenztest für Kinder - IV; LNS – Letter-Number sequencing; MPA – moderate physical activity; MVPA – moderate to vigorous physical activity; MPH – Methylphenidate; n.a. – not recorded; TEA-C - Test of Everyday Attention for Children; TMT – Trail Making Task; WCST – Wisconsin Card Sorting Test; WISC-R – Wechsler Intelligence Scale for Children – revised; * - *M* (age) of participants overall; ** - outcome measures included in this meta-analysis; *** - Interference Score; **** - Perseveration Error

		Intervention Group			Control Group			PA intervention						
Primary study	diagnosis	n	mean age (SD)	MPH intake	n	mean age (SD)	MPH intake	PA	duration	type	cognitive demand	Intensity	control group inter-vention	measures of EF **
Ziereis & Jansen (2015)	ICD-10	13	9.2 (1.3)	0	8	9.5 (1.4)	1	mixed PA incl. Ball games	3x60 min.; 12 weeks	aerobic	yes	n.a.	waiting list	HAWIK-IV (LNS)
Ziereis & Jansen (2015)	ICD-10	14	9.6 (1.6)	0	8	9.5 (1.4)	1	mixed PA incl. climbing	3x60 min.; 12 weeks	aerobic	no	n.a.	waiting list	HAWIK-IV (LNS)

CPT – Continuous Performance Test; DT - Discrimination Test; DST – Digit Span Task, HAWIK-IV - Hamburg-Wechsler-Intelligenztest für Kinder - IV; LNS – Letter-Number sequencing; MPA – moderate physical activity; MVPA – moderate to vigorous physical activity; MPH – Methylphenidate; n.a. – not recorded; TEA-C - Test of Everyday Attention for Children; TMT – Trail Making Task; WCST – Wisconsin Card Sorting Test; WISC-R – Wechsler Intelligence Scale for Children – revised; * - *M* (age) of participants overall; ** - outcome measures included in this meta-analysis; *** - Interference Score; **** - Perseveration Error

Table 3

Demographic data of groups included in the primary studies (n = 13).

	Total*	Experimental group			Control group**			PA intervention**		
	n	n	MPH intake	Age (*M*)	n	MPH intake	Age (*M*)	weeks	min./ session	times/ week
N***	13	13	11	11	12	11	11	13	13	13
Min	12	6	0	8.19	6	0	8.29	8	30	2
Max	60	24	20	14.50	25	17	14.20	78	90	3
n (total)	417	190	58		178	64		196	765	32
M	32.08	14.62	5.27	10	13.69	5.82	9.96	15.08	58.85	2.46
(*SD*)	(14.08)	(5.83)	(6.44)	(1.90)	(6.01)	(6.16)	(1.75)	(19.00)	(18.16)	(0.52)

*- All participants included in primary studies; **- according to data analysed in the primary studies. ***- Number of studies included in analysis of demographic data; Rezaei et al. (2019) did not provide information of age, or MPH intake; No information regarding MPH intake in groups (Da Silva et al., 2019)