Structured Physical Exercise Interventions and Children and Adolescents with Attention Deficit Hyperactivity Disorder: A Systematic Review and Meta-analysis

Fenghua Sun, PhD[1*a], Yuan Fang, PhD[1a], Carmen Ka Man Chan, MSocSc[1], Eric Tsz Chun Poon, PhD[1], Louisa Ming Yan Chung, DHSc, BSc[1], Peggy Pui Lai Or, PhD[1], Yajun Chen, PhD[2], Simon B. Cooper, PhD[3].

[1] Department of Health and Physical Education, The Education University of Hong Kong, Hong Kong SAR, China; [2] Department of Maternal and Child Health, School of Public Health, Sun Yat-sen University, Guangzhou, Guangdong, China; [3] Department of Sport Sciences, Sport, Health and Performance Enhancement (SHAPE) Research Centre, Nottingham Trent University, Nottingham, United Kingdom

[a] These authors contributed equally to this work.

* Correspondence author: **Dr. Fenghua Sun**
Email: fhsun@eduhk.hk
Address: Rm D4-2/F-25, The Education University of Hong Kong, No. 10 Lo Ping Road, Tai Po, New Territories, Hong Kong SAR, China

Abstract

Background: The efficacy of structured physical exercise (SPE) has been examined in empirical studies to treat attention deficit hyperactivity disorder (ADHD). This review aimed (i) to systematically review and quantify the effects of SPE on ADHD symptomology and executive function (primary outcomes), and on physical health, physical fitness, and mental health issues (secondary outcomes) in children/adolescents with ADHD; (ii) to evaluate the study quality and explore moderation of the effects of SPE; and (iii) to summarize the design of SPE interventions.

Methods: An extensive literature search in the databases of PubMed, Web of Science, and EBSCOhost was conducted to identify eligible intervention studies for meta-analysis. A descriptive account of the features of the studies are provided, including assessment of risk/quality (ROB-2/ROBINS-I). Standardized mean difference (SMD) with 95% confidence intervals (CI) were calculated with random effects models to compare post-intervention effects.

Results: A total of 18 studies were included in the review. The majority of the studies examined the effects of SPE lasting for 3-12 weeks. Assessment of bias/quality indicated half of the included studies as high quality. The meta-analysis (pooled n=627) revealed that SPE had a positive effect on primary and secondary outcomes, i.e., inattention (SMD=-1.79), executive function (SMD=2.19), physical fitness (SMD=1.39), and mental health issues (SMD=-0.89). Subgroup analysis showed that long-term practice of SPE, featured/tailored SPE, non-Chinese participants, taking methylphenidate, and study with low quality had larger effects.

Conclusions: There is emerging evidence that SPE is a promising option to enhance symptom management and physical/mental health in children/adolescents with ADHD.

Keywords:

Structured physical exercise; ADHD symptoms; executive function; physical health, physical fitness; mental health issues

Key Messages

1. Meta-analysis analyzed the effect of SPE on children/adolescents with ADHD.

2. Half of included studies were assessed as high quality.

3. Symptom reduction, executive function, and physical fitness were improved by SPE.

4. Moderators were program design, participants' characteristics, and study quality.

5. SPE is a promising option to treat and help children/adolescents with ADHD.

Introduction

As a neurodevelopmental disorder, attention deficit hyperactivity disorder (ADHD) has a global prevalence in children/adolescents as high as 5.9-7.1% (Huss et al., 2017; Núñez-Jaramillo et al., 2021). The core symptoms of ADHD are categorized into hyperactivity/impulsiveness and inattention, which may be presented with either one or combined (Wolraich et al., 2019). ADHD engages with the endophenotype functional impairements (e.g., executive dysfunction) and yields comorbid conditions of physical and/or mental illness in affected individuals (Huss et al., 2017; Liang et al., 2021).

So far, research has highlighted a complex of multiple genetic factors and non-inherited factors as sources of ADHD. As a polygenic condition, numerous genes are reported to essentially correlate to deficits of neuro-development and/or neurotransmission in ADHD (Núñez-Jaramillo et al., 2021). The non-inherited factors include those that may have occurred at different stages of central nervous system development since early embryogenesis, and include acute/chronic sleep disorders, changes in brain structure or brain injury (Núñez-Jaramillo et al., 2021; Thapar et al., 2012).

To manage and treat ADHD in children and adolescents, medication therapy and non-pharmaceutical interventions are common. A network meta-analysis reported comparative efficacy and tolerability of medications for individuals with ADHD in different age groups (Cortese et al., 2018). The study supported the use of methylphenidate (MPH) as the preferred choice for short-term pharmacological treatment of ADHD in children and adolescents. This is because MPH showed (1) greater improvements in both teacher- and clinician-rated ADHD core symptoms (i.e., reduction of excessive hyperactivity/impulsiveness and inattention, Núñez-Jaramillo et al., 2021; Taft Yazd et al., 2015) than placebo; and (2) better tolerability than placebo. However, previous evidence also calculated that the incidence of severe adverse events from taking MPH was 1/100 in children, with adverse events such as cardiac problems and psychiatric disorders (Storebø et al., 2018). In addition, more than 50% of MPH-treated ADHD patients suffered from at least one adverse event, such as decreased appetite, nausea, headache, insomnia, nasopharyngitis, dizziness, abdominal pain, irritability, and somnolence (Cerrillo-Urbina et al., 2018). Therefore, to avoid such adverse events, non-pharmaceutical treatments also play an important role in intervention design for children and adolescents with ADHD.

Recognized as one of the most efficient non-pharmaceutical approaches, physical activity was suggested to effectively reduce ADHD core symptoms and enhance neurofunctions in children with ADHD (Cerrillo-Urbina et al., 2015; Jeyanthi et al., 2019). A meta-analysis of randomized controlled trials indicated that the effect of moderate-to-vigorous physical activity on total ADHD core symptoms was −0.33 (Hedges' *g*, Seiffer et al., 2021). Furthermore, Lambez et al. (2020) reported that physical activity had the largest effect size (Morris' d: 0.93) for improvements in cognitive function in the population with ADHD, when it was compared to other types of non-pharmaceutical treatments (i.e., Morris' d for neurofeedback, cognitive-behavioral therapy, and cognitive training were 0.61, 0.70, and 0.45, respectively). It is also important to emphasize that no adverse effects were reported during physical exercise interventions in populations with ADHD (Ng et al., 2017).

Moreover, the previous literature showed that either single bout or long-term practice of physical activity (PA) may contribute to the improvement in cognition and behavior of children/adolescents with ADHD. According to the meta-analysis of Suarez-Manzano et al. (2018), a PA practice at 20-30 min with intensity of 40-75% may produce the positive acute effect on cognitive processing speed, working memory, planning, and problem-solving in children/adolescents with ADHD. In addition to this, they may further improve their attention, inhibition, emotional control, behaviour and motor control by taking a long-term PA practice at ≥30 min/day, ≥40% intensity, ≥3 days/week, ≥5 weeks.

The current study focuses on a particular type of physical activity - structured physical exercise (SPE). SPE is defined as a planned, supervised, and controlled/monitored physical activity program (Taylor et al., 2018; Umpierre et al., 2011). Evidence from reported RCTs showed that adolescents enhanced executive function (i.e., the ability of self-regulating cognition, speaking, action, emotion, attention and memory to complete tasks) due to the incorporation of more complex and goal-directed exercise in SPE programs (Schreiber et al., 2014). Particularly, a greater improvement in the results of neurocognitive tests was observed in adolescents following long-term practice of SPE programs (i.e., weeks to months), when compared to a control group (Subramanian et al., 2015; Wasenius et al., 2014). Moreover, Sharma et al. (2017) also revealed that SPE was beneficial for adolescents' physical health in terms of cardiorespiratory capacity, heart rate variability (HRV), and reduction of body fat. Therefore, SPE clearly has great potential from a health promotion perspective (Halperin et al., 2014).

A growing number of SPE interventions in ADHD treatment have been studied. For example, a quasi-experiment conducted in Tunisian children with ADHD (Hattabi et al., 2019) adopted a 12-week (3 x 90 min sessions per week), moderate-intensity aquatic SPE. The experimental group in the study showed a significant improvement in memory accuracy, selective attention, and inhibition process than participants in the inactive control group ($p<0.001$). Another recent Iranian RCT examined the effectiveness of a 6-week (3 sessions per week) structured high-intensity interval training (HIIT) program in adolescents with ADHD (Soori et al., 2020). The findings demonstrated significantly greater improvements in the intervention group, compared to the control group (i.e., routine care). These included parent-reported ADHD core symptoms assessment (p=0.040), body mass index (BMI) z-score and body fat mass (BFM) (p<0.001 and p=0.019, respectively), and reduction in the level of interleukin-13 (i.e., IL-13, a peripheral inflammatory mediator related to obesity, p=0.017). This was evident that reduction in core symptoms, enhancement of executive function, and improvement of physical health were achieved in children/adolescents with ADHD after they attended the SPE programs.

Given the multi-faceted benefits of SPE, their efficacy within children/adolescents with ADHD was measured by different indicators/methodologies in the literature. This resulted in barriers of comparing the effects of studies and knowledge gaps in potential moderators. Therefore, a systematic review and meta-analysis is warranted to summarize and compare the effects reported by those empirical studies, where a formal test of moderation is also sought to conduct. The exploration of potential moderators in the targeted effect may indicate the relationship between the variation of studies and effect sizes (e.g., medication status of participants, ethnicity of participants, program design, study quality, etc.). Thus, findings of moderator analysis may suggest whether SPE is more effective for some specific groups of children/adolescents with ADHD than others or it is only effective under some conditions than others.

Objectives

The aims of this systematic review and meta-analysis are (i) to systematically review and quantify the effects of SPE on ADHD symptomology and executive function (primary outcomes) and on physical health, physical fitness, and mental health (secondary outcomes) in children/adolescents with ADHD; (ii) to evaluate the quality of reviewed studies and explore moderation of the effects of SPE; and (iii) to summarize the design of SPE interventions.

Methods

Search strategy

The current review was registered in PROSPERO (CRD42022352895). Relevant journal articles were identified by searching the electronic databases from PubMed, Web of Science, and EBSCOhost, which are database/platforms covering the published periods of 1966-2022, 1975-2022, and 1929-2022 respectively. The Boolean operator was used in the search strategy with "OR" and/or "AND" used to link search terms, while the asterisk "*" was used as a wildcard symbol appended at the end of the terms to search for variations of those terms. The complete search strategy in title/abstract/topic is shown in **Table 1**.

Two authors were involved in the articles screening, whereas a consensus by comparison or discussion was made between the authors during the process. Articles were screened for relevance through reviewing titles and abstracts. After removing the duplicates and excluding those that did not meet the inclusion criteria, the remaining 103 articles were read in full to identify if they met the inclusion criteria. In addition, another 5 research papers were included by checking through the reference lists of previously published systematic reviews in relevant research areas. Finally, 18 articles, which provided sufficient data for comparing effect sizes, were included in this systematic review and meta-analysis.

Inclusion and exclusion criteria

Inclusion criteria for the review were that included studies had to (i) have an experimental design (quasi- or true-); (ii) be conducted with children/adolescents diagnosed with ADHD; (iii) have SPE as intervention; (iv) be published in English-speaking journals; and (v) report sufficient data of selected post-intervention outcomes to calculate/compare in meta-analysis. An article was excluded if (1) it was with a non-experimental design; (2) it reported the development/validation of a scale/tool; (3) participants were adults; (4) participants did not have a clinical diagnosis of ADHD; (5) participants were athletes or soldiers/military recruits/veterans with ADHD; (6) participants had a history of brain injury; (7) the intervention was not designed in compliance with the definition of "structured physical exercise"; (8) the study focused on the effect of interventions other than physical exercise (e.g., medication); (9) the intervention program had potential features/attractions in addition to physical exercise, e.g., mindfulness-based interventions, exergames, or equestrian therapies, etc.; (10) the study focused on roles of parents/health professionals; or (11) the study is lack of sufficient information to compare the effect sizes of selected post-intervention outcomes in the meta-analysis (including those studies that we failed to receive response from authors).

Assessment for publication quality and risk of bias

Risk of bias from the included articles was assessed by ROB 2 for RCTs (Sterne et al., 2019) and ROBINS-I for quasi-experiments (Sterne et al., 2016). The results are categorized as low risk, some concerns, and high risk (**Table 2)**. The assessment was determined for each item by two authors, reaching a consensus by comparison or discussion as necessary. Finally, in subgroup analysis, studies were further grouped in high risk if they were evaluated as having "some concerns" or "high risk" in quality assessments (**Table 2**); otherwise, the study was listed as low risk.

Data extraction

Relevant information from the included articles was analysed and summarised using a standardized table with categorized themes of key information (see **Table 3**). This table includes the published year, country, study design, background information of the sample, program protocol in both the intervention and control group (i.e., modality, duration and content), and effectiveness of designed programs in terms of the utilized measures and key results. Two authors independently completed the review process and data extraction, with a consensus regarding final study inclusion, analyses and summary achieved via discussion.

Data analysis and synthesis

RevMan 5.4.1 (The Cochrane Collaboration, Software Update, Oxford, UK) was used to conduct the meta-analysis. The extracted outcomes of post-intervention were operationalized as continuous measures for comparison, which may result in a high level of heterogeneity potentially existing between different studies. Thus, the standardized mean difference (SMD, calculated as Hedge's adjusted *g* with adjustment of small sample bias, Deeks & Higgins, 2010) with 95% Confidence Intervals (CI) was calculated using a random effect model. In the analysis, significance was set as $p<0.05$. To interpret the result of the meta-analysis, SMD (95% CI) was perceived as trivial (0.00-0.19), small (0.20-0.49), medium (0.50-0.79) and large (≥0.80), as per convention (Cohen, 2013; Hedges, & Olkin, 1985). Subgroup analyses were also conducted by a random effect model. The *Q* statistic test was used in this study and set as significant when $p<0.05$. For the meta-analysis of a small number of included studies, *Q* statistic test is a comprehensive test of the homogeneity of effect sizes and the impact of moderators (Cochran, 1954). Furthermore, the amount of heterogeneity (%) was assessed by I^2 statistic test, whereas the increasing I^2 value represented an increased heterogeneity in the particular subgroup, which was interpreted as small (<25%), medium (25-75%), or large (>75%), as per convention (Higgins et al., 2003).

Assessment of publication bias

The potential publication bias of selected endpoints was presented by the funnel plots with SMD as x-axis and the standard error of SMD as y-axis. All endpoints were further assessed by Egger's test to detect the asymmetry of funnel plots (Egger et al., 1997). Moreover, the trim-and-fill method was used to estimate the true effect size adjusted by potential publication bias and the number of studies needed to balance the funnel plot (Duval & Tweedie, 2000). Significance was set as $p<0.05$ for all tests.

Results

Overview of included studies

The Prisma flow diagram describing the search process is presented in **Figure 1**. A total of 18 papers published between 2011 and 2021 were included in the systematic review and meta-analysis (see **Table 3**). Among the 18 included studies, 16 papers reported the long-term practice of SPE programs among children/adolescents with ADHD, whereas 2 papers focused on single-bout of SPE. Among them, 11 studies involved RCTs and 7 studies used quasi-experimental designs. Regarding the study setting, 13 studies were conducted in a research setting (e.g., laboratory), and the other 5 were targeted at a school setting (including one combined with a home setting).

Of the included articles, (a) studies covered 9 countries/regions; (b) all participants were clinically diagnosed with ADHD including 627 children/adolescents (i.e., aged in 6-16 years old, 417 boys and 119 girls, as well as 91 children for whom gender was not reported); and (c) half of included studies that involved participants who were totally or partially on medication during the intervention (e.g. MPH), while 4 studies included those who were not on medication, whereas another 5 studies did not report the medication status of their participants.

Risk of bias and study quality

According to RoB 2 and ROBINS-I (**Table 2)**, it showed that (1) nine RCTs had a low risk of bias, (2) two RCTs and six quasi-experiments were assessed as having some concerns in assessment, and (3) one quasi-experiment was evaluated to have a high risk of bias. In the related RCTs and quasi-experiments, some concerns were raised in the evaluation terms of missing outcome data and measurement of the outcomes. For the one study with a high risk of bias (Ardakani & Ardakani, 2020), selection of participants, deviations from intended interventions, and selection of reported result was further evaluated as having "high risk" or "some concerns".

Design of SPE implemented in the included studies

Of 18 included studies, (a) 17 programs possessed a clearly planned curriculum, of which 15 programs followed three structured phases, i.e., warm-up, main exercises, and cool-down; (b) 8 programs with long-term practice were reported to receive supervision or instruction from physical activity professionals (e.g., coaches, teachers, etc.); and (c) physiological indicators were monitored during the interventions of 8 programs with long-term practice and 2 single-bout of SPE (e.g., heart rate, VO_2max, and/or perceived exertion, etc.). The activities in the control groups included routine care, inactive/active control, or sedentary activities. (**Table 3**).

There were extensive differences in the physical exercises of included studies in regard to duration, frequency, sport types, structure, and intensity. Apart from single-bout of SPE, the programs with long-term practice had the dosage of interventions ranged in 3-12 weeks, and 9-36 total sessions (40-90 mins per session). Beside of one study focused on the dose-response relationship of exercise intensity (Memarmoghaddam et al., 2016), there were 3 studies utilising high-intensity SPE, 4 moderate-to-vigorous intensity, and 4 moderate intensity. Among these studies, SPE programs with long-term practice tended to use higher intensity than single-bout of SPE, i.e., three HIIT programs were conducted in 3-6 weeks (Meßler et al., 2018; Soori et al., 2020; Torabi et al., 2018); while single-bout SPE adopted moderate intensity aerobic exercise (Chang et al., 2012; Hung et al., 2016).

Results of the meta-analysis

A summary of results of the meta-analysis is presented in **Table 4**, and the forest plots of all outcomes are shown in **Online supplementary material Figure S1-S5**.

Primary outcomes

ADHD symptomology. The meta-analysis provided evidence to support the positive large effects of SPE on ADHD symptomology among children/adolescents with ADHD. Based on the parent-reported data of 151 participants (n=80 intervention and n=71 control), the SMD of overall ADHD symptoms was -0.97 (large effect, 95% CI -2.26 to 0.32, p=0.14) with large heterogeneity (I^2=92%, p<0.001). In particular, inattention (SMD=-1.79, 95% CI -3.28 to -0.30, p=0.02, large effect; I^2=88%, large heterogeneity, p<0.001) showed a significant reduction among 96 participants (n=48 intervention and n=48 control).

Executive function. The meta-analysis also supported SPE programs as having a significant positive large impact on the executive function of children/adolescents with ADHD. Based on the analysis (n=279 intervention and n=279 control), the pooled SMD of overall executive function was 2.19 (large effect, 95% CI 1.41 to 2.98, $p<0.001$) with large heterogeneity ($I^2=92\%$, $p<0.001$). Specifically, response inhibition (SMD=1.99, 95% CI 1.34 to 2.63, $p<0.001$, large effect; $I^2=60\%$, medium heterogeneity, $p=0.06$) and selective attention (SMD=1.70, 95% CI 0.56 to 2.85, $p=0.004$, large effect; $I^2=84\%$, large heterogeneity, $p<0.001$) presented significant improvement in the intervention group compared to the control group, whereas cognitive flexibility (SMD=2.24, 95% CI 0.03 to 4.45, $p=0.05$, large effect; $I^2=96\%$, large heterogeneity, $p<0.001$) and memory function (SMD=3.14, 95% CI -0.35 to 6.64, $p=0.08$, large effect; $I^2=97\%$, large heterogeneity, $p<0.001$) demonstrated marginal improvement in those participants after SPE, albeit with very large effect sizes.

Secondary outcomes

Physical health. The SMD of BMI was -0.14 (trivial effect, 95% CI -0.48 to 0.20, $p=0.43$) with small heterogeneity ($I^2=17\%$, $p=0.31$) based on 91 and 78 participants of intervention and control groups respectively.

Physical fitness. The meta-analysis indicated that the SPE programs had a positive large impact on the fitness level of individuals with ADHD. Based on the enrolled studies, there were total of 216 and 212 participants respectively assigned to the intervention group and control group, whereas the pooled SMD of overall fitness level was 1.39 (large effect, 95% CI 0.98 to 1.80, $p<0.001$) with medium-large heterogeneity ($I^2=69\%$, $p<0.001$). Particularly, both aerobic capacity (SMD=1.81, 95% CI 0.98 to 2.64, $p<0.001$, large effect; $I^2=73\%$, medium-large heterogeneity, $p<0.001$) and motor skills (SMD=1.39, 95% CI 0.98 to 1.80, $p<0.001$, large effect; $I^2=58\%$, medium heterogeneity, p=0.01) were significantly enhanced in intervention participants when compared to those in control groups.

Mental health issues. For mental health issues (n=88 intervention and n=88 control), the pooled SMD was -0.89 (large effect, 95% CI -1.57 to -0.21, p=0.01) with large heterogeneity (I^2=76%, p<0.001). More specifically, depression (SMD=-1.67, 95% CI -2.87 to -0.47, p=0.006, large effect; I^2=81%, large heterogeneity, p=0.002) showed significant reduction in the intervention group compared to control group, whereas anxiety (SMD=-0.22, 95% CI -0.77 to 0.32, p=0.43, small effect; I^2=37%, small-medium heterogeneity, p=0.19) showed no significant difference between the intervention group and control group.

Potential moderators

As summarized in **Table 4**, program design, study quality, participants' ethnicity, and MPH use in participants were assessed as the potential moderators to explain the heterogeneity of the main effects reported above. For program design, (1) participants involved in the programs with motor skills training showed significantly greater improvements in motor skills (SMD=1.91, 95% CI 1.32 to 2.51, p<0.001, large effect; I^2=0%) than those enrolled in the programs with other focuses such as executive function or high intensity (SMD=0.74, 95% CI 0.47 to 1.02; p<0.001, medium effect; I^2=0%); (2) similarly, overall ADHD symptoms of participants showed significantly greater improvements in the program with perceptual training (SMD=-3.23, 95% CI -4.09 to -2.37, p<0.001) than those without (SMD=-0.27, 95% CI -0.66 to 0.13, p=0.19, small effect; I^2=0%); and (3) the programs with long-term practice derived significant improvements in cognitive flexibility (SMD=3.13, 95% CI 0.67 to 5.59, p=0.01, large effect; I^2=93%, p<0.001) and memory function (SMD=4.70, 95% CI 3.87 to 5.53, p<0.001, large effect; I^2=0%) when it was compared with single-bout of SPE (SMD of cognitive flexibility: -0.30, 95% CI -0.93 to 0.32, p=0.34, small effect; SMD of memory function: 0.02, 95% CI -0.65 to 0.69, p=0.96, trivial effect). For study quality, studies appraised as low quality showed significantly larger effect on reduction in depression (SMD=-2.24, 95% CI -2.94 to -1.54, p<0.001, large effect; I^2=0%) and inattention (SMD=-3.56, 95% CI -4.69 to -2.42, p<0.001, large effect; I^2=0%) of ADHD participants than studies assessed as high quality (SMD of depression: -0.26, 95% CI -0.96 to 0.44, p=0.46, small effect; SMD of inattention: -0.40, 95% CI -0.91 to 0.11, p=0.13, small effect; I^2=0%). Study quality also affected the effect of SPE programs on improving aerobic capacity among participants (SMD=2.41 in low-quality studies, 95% CI 1.86 to 2.95, p<0.001, large effect; I^2=0%; while SMD=0.60 in high-quality studies, 95% CI -0.04 to 1.24, p=0.07, medium effect; I^2=0%). Regarding ethnicity of participants, non-Chinese participants (SMD=4.33, 95% CI 3.44 to 5.23, p<0.001, large effect; I^2=0%) showed significantly larger effect in cognitive flexibility than Chinese participants (SMD=0.36, 95% CI -0.98 to 1.70, p=0.60, small effect; I^2=86%, p=0.007). Furthermore, participants with confirmed MPH use demonstrated significantly greater improvements in selective attention (SMD=2.14, 95% CI 1.48 to 2.80, p<0.001, large effect; I^2=0%) than their counterparts who did not take MPH (SMD=0.50, 95% CI 0.06 to 0.93, p=0.03, medium effect).

Publication bias

Moreover, the potential publication bias is presented by funnel plots (**Online supplementary material Figure S6-S11**) and was assessed by both Egger's test and the trim-and-fill method. Based on Egger's test, publication bias was not statistically significant (p>0.05) when program design, study quality, ethnicity of participants and MPH use was adjusted in the relevant outcomes (see **Table 4**). This indicated they were also the potential moderators of relevant publication bias in such outcomes. Furthermore, after inputting the studies that helped to balance the funnel plots, the adjusted effect sizes of SPE were obtained in inattention (-1.37, 95% CI -3.09 to 0.36, large effect), selective attention (1.36, 95% CI 0.31 to 2.41, large effect), motor skill (0.90, 95% CI 0.42 to 1.37, large effect), and depression of participants (-1.46, 95% CI -2.37 to -0.55, large effect).

Discussion

This study focused on SPE specifically designed for children/adolescents with ADHD. Most findings of this review provided a preliminary evidence for the effect of SPE on ADHD treatment in the affected children/adolescents (**Table 4**).

First, SPE programs showed a significant large effect on ADHD symptomology in this meta-analysis (i.e., overall ADHD symptoms and inattention). However, subgroup analysis revealed that featured program design significantly increased the effect of SPE on overall ADHD symptoms ($p_{subgroup}$<0.001), i.e., a large effect was found in one SPE program with perceptual training (SMD=-3.23, p<0.001, Kouhbanani & Rothenberger, 2021) whereas a non-significant small effect was obtained based on other three programs without perceptual training (SMD=-0.27, p=0.19, I^2=0%). Moreover, the increase of study quality significantly decreased the effect of SPE programs on inattention ($p_{subgroup}$<0.001, SMD was -3.56 in studies with low quality while it was -0.40 in studies with high quality). This finding is consistent with the literature that biased studies are more likely to overestimate the effects of treatment (Gluud, 2006; Deeks et al., 2003). Besides, since the effect of SPE on hyperactivity/impulsiveness was assessed in only one included study (SMD=-0.33, p=0.39, small effect, Meßler et al., 2018), it was not involved in the meta-analysis.

Second, results of the present meta-analysis demonstrated that SPE programs showed a significant large effect on executive function, especially in response inhibition (SMD=1.99,

$p<0.001$, $I^2=60\%$) and selective attention (SMD=1.70, $p<0.01$, $I^2=84\%$). Compared with the literature (SMD: 0.76-1.30 in Liang et al., 2021; Zhang et al., 2020), SPE had a larger effect on response inhibition than mixed types of physical exercises/activities. Particularly, the subgroup analysis indicated that taking MPH significantly ($p_{subgroup}<0.001$) increased the selective attention of children/adolescents with ADHD during their participation in SPE programs (SMD=2.14, $p<0.001$, $I^2=0\%$), which is in line with the findings of previous literature (Cortese et al., 2018). In addition, SPE programs with long-term practice had a significantly larger effect than the single-bout of SPE on cognitive flexibility (SMD=3.13 vs -0.13, $p_{subgroup}<0.01$) and memory function (SMD=4.70 vs 0.02, $p_{subgroup}<0.001$) of children/adolescents with ADHD. This was supported by the previous findings that a higher dosage of physical activity/exercise was associated with larger benefits for improvement in participants with ADHD (Halperin et al., 2014; Suarez-Manzano et al., 2018). Also, it was found in subgroup analysis that non-Chinese participants had a significantly better response ($p_{subgroup}<0.001$) in cognitive flexibility (SMD=4.33, $p<0.001$, $I^2=0\%$) by SPE interventions when they were compared with those Chinese participants (SMD=0.36, $p=0.60$, $I^2=86\%$). It implied a novel finding by this study - a tailored SPE intervention may be required for children/adolescents with ADHD based on their ethnicities. Cultural context may potentially play some role in the effectiveness of intervention.

Third, regarding the effect on physical health of children/adolescents with ADHD, a trivial effect was revealed for SPE programs to reduce BMI (SMD=-0.14, $p=0.31$, $I^2=17\%$) in this meta-analysis. This may be due to the fact that the use of BMI in children and adolescents has limitations, because the processes of growth and maturation were still ongoing (Vanderwall et al., 2017).

Fourth, the included SPE programs presented a large effect on physical fitness in terms of aerobic capacity (SMD=1.81, $p<0.001$, $I^2=69\%$) and motor skills (SMD=1.08, $p<0.001$, $I^2=49\%$).

According to the subgroup analysis, study quality significantly affected the effect of SPE programs on aerobic capacity of participating children/adolescents ($p_{subgroup}$<0.001), i.e., high-quality studies showed a non-significant medium effect (SMD=0.60, p=0.07, I^2=0%) whereas biased studies demonstrated a significant large effect (SMD=2.41, p<0.001, I^2=0%). For the effect on motor skills, SPE programs targeting on motor skill training significantly ($p_{subgroup}$<0.001) increased the intervention effect (SMD=1.91, p<0.001, I^2=0%) when it was compared with those programs with other focuses (SMD=0.74, p<0.001, I^2=0%). This implied that featured program design was efficient to improve the relevant functions of children/adolescents with ADHD.

Fifth, a controversial result was obtained in this meta-analysis regarding reduction of mental health issues in participants of SPE programs. On one hand, a significant large effect and a large heterogeneity were observed in the effect of SPE on reducing depression (SMD=-1.67, p<0.001, I^2=76%). Once again, subgroup analysis showed that biased studies significantly ($p_{subgroup}$<0.001) overestimated the effect of intervention (SMD=-2.24, p<0.001, I^2=0%). However, the high-quality study showed a non-significant small effect on depression reduction in participants of SPE program (SMD=-0.26, p=0.46, Pan et al., 2016). On the other hand, SPE programs had a non-significant small effect on decreasing anxiety in the participating children/adolescents with ADHD (SMD=-0.22, p=0.43, I^2=37%). Thus, an extensive and comparable evidence was desired to investigate the benefit of SPE for mental well-being of children/adolescents with ADHD.

At last, according to the assessments of publication bias, six outcomes were tested as significantly-potential for having publication bias in Egger's test (see **Table 4**), whereas the moderators were explored. Further estimation of the true effect sizes was conducted by the trim-and-fill method in correction of the publication bias for these six outcomes. Effect sizes of SPE were remained with no change for cognitive flexibility and memory function in children/adolescents with ADHD; while the smaller adjusted effect sizes were estimated for inattention, selective attention, motor skills, and depression of participants. This indicated the evidence of publication bias in the included studies.

Limitations

There are several limitations acknowledged in this study. First, due to the limited number of included studies in this review, comparable data was limited and different measures of a construct were inevitably combined, whereas a large heterogeneity and publication bias were observed in half of the study outcomes. Additionally, the publication bias in this study may not be accurately assessed because less than 10 included studies were used to compare for each outcome (Sterne et al., 2011). Thus, findings of this study are considered as a preliminary evidence for the effect of SPE on ADHD treatment among affected children/adolescents. Second, most of the included studies had a small sample size, which may limit the generalization of the findings. Third, quality of the included studies is another key consideration which was discussed frequently in subgroup analysis. Although RCTs possessed an advantage in obtaining high-quality data over quasi-experiments, there are still some concerns in the two criteria of assessment for both RCTs and quasi-experiments. One concern is the lack of some information in the included studies, i.e., whether outcome assessors were aware of the intervention received by study participants, and whether the assessment of the outcome was likely to have been influenced by knowledge of intervention received. This related to the self-reported data which was influenced by recall bias or social-desirability bias (i.e., data reported by parents or teachers who were not blinded to intervention). Another concern is that the interpretation of missing data was unclear in some studies. This may raise the risk of bias because missingness was likely to depend on its true value and/or a reflection of problematic reach related to the program design. Fourth, the background information of participants was unclear or unbalanced in some included studies, i.e., a narrow age range hindered the generalization to other age ranges; and an unclarified effect of taking medication during the intervention may confound intervention effects. Finally, the articles were retrieved from eighteen electronic databases, the selected studies were limited for reviewing because (i) only those with specific terms mentioned in the title/abstract were screened for further analyses; (ii) those in a non-English language, with the publication forms as conference abstract, government report, textbook, or unpublished dissertation were not included.

Conclusion

The current review focused on the effect of SPE on ADHD treatment in affected children/adolescents. The meta-analysis of 18 included studies provided a preliminary evidence for the effect of SPE, which was also further interpreted by subgroup analysis. Results showed that SPE had a positive effect on reducing ADHD symptomology, improving executive function, enhancing physical fitness, and decreasing mental health issues. Subgroup analysis implied that (i) a featured SPE program design is promising for improving particular functions, (ii) long-term practice of SPE benefited for ADHD treatment more than single-bout of SPE, and (iii) a tailored SPE program may be required according to the different ethnicity of participants. Consistently, MPH use significantly increased the positive effect of SPE in the selective attention of participating youth. Future research is also warranted to evaluate SPE programs in studies adopting a larger sample size and a high study quality, whereas implementing a comprehensive program design may bring benefits to this vulnerable population.

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Figure.

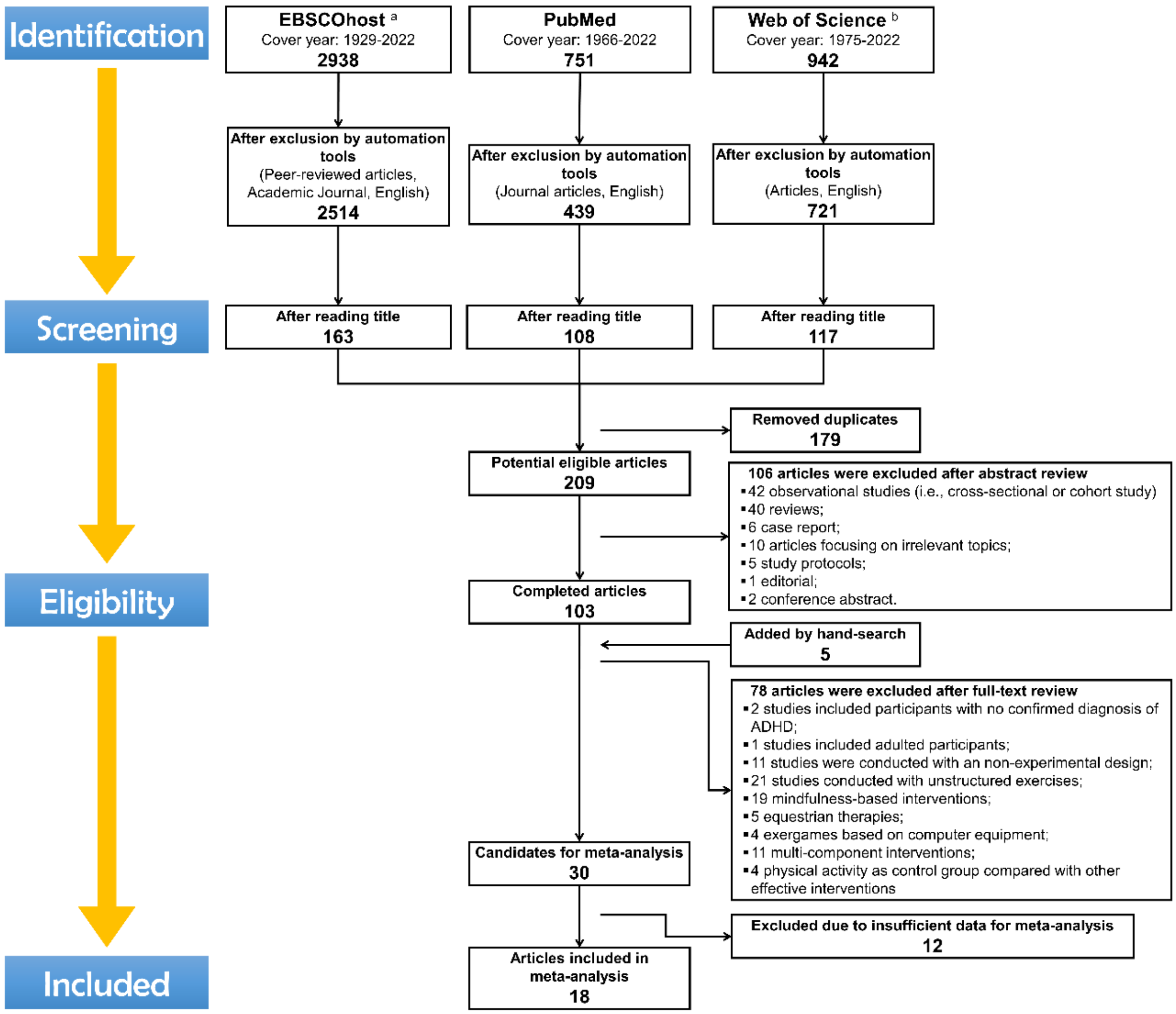


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram: Search process for studies selection about structured physical exercise programs for children and adolescents with ADHD.

[a] Included databases of EBSCOhost are Academic Search Alumni Edition, Academic Search Ultimate, British Education Index, CINAHL with Full Text, Education Full Text (H.W. Wilson), Education Index Retrospective: 1929-1983 (H.W. Wilson), Education Research Complete, ERIC, MAS Ultra - School Edition, MEDLINE, Primary Search, APA PsycArticles, APA PsycInfo, SPORTDiscus with Full Text, Teacher Reference Center; [b] Included databases of Web of Science are SSCI and A&HCI.

Tables.

Table 1. Search strategy.

No.	Terms
1	"physical activit*" OR "exercise*" OR "fitness" OR "physical exercise*" OR "sport*" OR "walk*" OR "cycling" OR "swim*" OR "aqua*" OR "water*" OR "HIIT" OR "High Intensity Interval Training"
2	"ADHD" OR "attention deficit-hyperactivity disorder" OR "attention deficit hyperactivity disorder"
3	"effect*" OR "impact" OR "consequence*" OR "influence*" OR "outcome*" OR "efficacy" OR "benefit*" OR "improvement" OR "success" OR "performance" OR "function*"
4	1 AND 2 AND 3

Table 2. Quality assessment of included studies.

a. RCTs (assessed by ROB 2)

No.	Ref	Randomization Process	Deviations from the intended interventions	Missing outcome data	Measurement of the outcome	Selection of the reported result	Overall risk-of-bias judgement
1	Kouhbanani & Rothenberger, 2021	Low	Low	Low	Low	Low	Low
2	Da Silva et al., 2020	Low	Low	Some concerns	Some concerns	Low	Some concerns
3	Durgut, Orengul, & Algun, 2020	Low	Low	Low	Low	Low	Low
4	Soori et al., 2020	Low	Low	Low	Low	Low	Low
5	Meßler, Holmberg, & Sperlich, 2018	Low	Low	Low	Low	Low	Low
6	Memarmoghaddam et al., 2016	Low	Low	Some concerns	Some concerns	Low	Some concerns
7	Pan et al., 2016	Low	Low	Low	Low	Low	Low
8	Lee, Lee, & Park 2015	Low	Low	Low	Low	Low	Low
9	Taft Yazd et al., 2015	Low	Low	Low	Low	Low	Low
10	Ahmed & Mohamed, 2011	Low	Low	Low	Low	Low	Low
11	Chang et al., 2012	Low	Low	Low	Low	Low	Low

b. Quasi-experiments (assessed by ROBINS-I)

No.	Ref	Confounding	Selection of participants into the study	Classification of interventions	Deviations from intended interventions	Missing data	Measurement of outcomes	Selection of the reported result	Overall risk-of-bias judgement
12	Ardakani & Ardakani, 2020	Some concerns	High	Low	High	Low	Some concerns	Some concerns	High
13	Hattabi et al., 2019	Some concerns	Low	Low	Low	Low	Some concerns	Low	Some concerns
14	Pan et al., 2019	Some concerns	Low	Low	Low	Low	Some concerns	Low	Some concerns
15	Torabi et al., 2018	Some concerns	Low	Low	Low	Low	Some concerns	Low	Some concerns
16	Kosari et al., 2013	Some concerns	Low	Low	Low	Low	Some concerns	Low	Some concerns
17	Verret et al., 2012	Some concerns	Low	Low	Low	Low	Some concerns	Low	Some concerns
18	Hung et al., 2016	Some concerns	Low	Low	Low	Low	Some concerns	Low	Some concerns

Table 3. Basic information of included studies in systematic review and meta-analysis.

No	Ref	Country / Study design / Setting	Sample		Programme design (modality, duration and content)		Effectiveness of intervention
			Subjects	Medicated during study	Intervention group	Control group	
SPE programs with long-term practice							
1	Kouhbanani & Rothenberger, 2021	Iran RCT Research	50 children with ADHD (aged 8-10 years, 32 boys and 18 girls): 25 in experimental group, 25 in waiting control group.	No	❖ Perceptual-motor skills reconstruction training; 6 weeks; 3x/week in first 5 weeks and 1x/week in the 6th week; 45 mins/session. ❖ The training was monitored and supervised by 3 PA teachers.	Routine care	• Executive Functions (Delis-Kaplan Executive Function System): positive effect*; • ADHD symptoms (CPRS-r): positive effect.
2	Ardakani & Ardakani, 2020	Iran Quasi-experimental design Research	21 children with ADHD (aged 7-12 years old, 19 boys and 2 girls)	Yes	❖ The structured group paintball program; 10 weeks; 3x/week; 45 mins/session (including warm-up, main training, cool-down). ❖ Heart rate was monitored once a week for each child.	NA	• Fitness and motor skills (anthropometrical and fitness tests): positive effect; • Behavioral measures (CBCL): positive effect*; • Neuropsychological measures (Sky search test): positive effect*.
3	Da Silva et al., 2020	Brazil RCT School	20 adolescents with ADHD (aged 11-14 years old, 14 boys and 6 girls): 10 in trained group, 10 in untrained group.	Yes	❖ Swimming-learning lessons; 8 weeks; 2x/week; 45 min/session (including warm-up, swimming-learning exercises, recreational activity, cool-down).	Inactive	• Mental health (CDI, BAI, PSS-14): positive effect*; • Cognitive flexibility (Test of trails): positive effect*; • Attention function (TAC Cancellation Attention Test): positive effect*; • Motor coordination (fitness tests): positive effect*.
4	Durgut, Orengul, & Algun, 2020	Turkey RCT Research	30 children with ADHD (7-11 years old, 15 in experimental group, 15 in control group)	NA	❖ Whole body vibration training (WBVT) and treadmill training (TT); 8 weeks; 3x/week; 15 mins WBVT and 45 mins TT/session (including warm-up, training and cooling down). ❖ Heart rate was monitored during the training.	Treadmill training (TT): same as experimental group	• Executive function (Stroop test, BRIEF): positive effect*; • ADHD symptoms (CPRS): positive effect*; • Quality of life (PedsQL): positive effect.
5	Soori et al., 2020	Iran RCT Research	43 adolescents with ADHD (mean aged at 12.55-12.5 years old, 20 boys and 23 girls): 26 in intervention group, 17 in control group.	No	❖ HIIT intervention; 6 weeks; 3x/week; Each training session including warm-up, HIIT main stage and cool-down. ❖ Heart rate was monitored and targeted at 85% max heart rate during HIIT training.	Routine care	• Fitness level (BMI, BFM, clinical parameters): positive effect*; • ADHD symptoms (CPRS): positive effect*.
6	Hattabi et al., 2019	Tunisia Quasi-experimental design Research	40 children with ADHD (mean aged 9.95-9.75 years old): 20 in training group, 20 in control group.	NA	❖ Moderate-intensity water aerobic exercise intervention; 12 weeks; 3x/week; 90 mins/session (including warm-up, main training, cool-down). ❖ The training was conducted by three professional instructors. ❖ Heart rate was monitored during the intervention.	Inactive	• Memory function (ROCF): positive effect*; • Response inhibition (Stroop test, Hayling test): positive effect*.
7	Pan et al., 2019	Taiwan, China Quasi-experimental design School	30 boys with ADHD (aged 7-12 years): 15 in ADHD training group, 15 in ADHD non-training group.	Yes	❖ The table tennis program; 12 weeks; 2x/week; 70 mins/session (including warm-up, main training, cool-down). ❖ The program was supervised by primary researcher of this study.	Inactive	• Motor skills (TGMD-2): positive effect*; • Executive functions (Stroop test, WCST): positive effect*.
8	Meßler, Holmberg, & Sperlich, 2018	Germany RCT Research	28 boys with ADHD (aged 8-13 years old): 14 in HIIT group, 14 in TRAD group.	Partially	❖ Multimodal HIIT intervention; 3 weeks; 3x/week; each session included warm-up and four 4-min sessions of exercise. ❖ Heart rate was monitored during intervention while HIIT exercise was targeted at 95% HRpeak with 3-min intervals at <60% HRpeak.	Traditional low-moderate intensity exercise therapy (standard); 3 weeks; 3x/week; 60 mins/session.	• Physical fitness (Maximal power output, peak oxygen uptake, oxygen uptake): positive effect; • Motor skills (M-ABC-II): positive effect; • Quality of life (KINDL): positive effect*; • ADHD symptoms (parent-rated and self-rated questionnaire): positive effect.
9	Torabi et al., 2018	Iran Quasi-experimental design Research	50 adolescents with ADHD (mean aged 12.7±1.08 years old, 30 girls and 20 boys): 25 in experimental group (15 girls	NA	❖ HIIT program; 6 weeks; 3x/week; each session included warm-up, HIIT main stage, cool-down (HIIT stage included 20 meter running repetitions with 30-20 second resting between intervals).	Inactive	• Motor proficiency (BOTMP): positive effect* (for both genders); • Biochemical evaluation (adiponectin, insulin resistance): positive effect* (for both genders);

No	Ref	Country / Study design / Setting	Sample		Programme design (modality, duration and content)		Effectiveness of intervention
			Subjects	Medicated during study	Intervention group	Control group	
			and 10 boys), 25 in control group (15 girls and 10 boys).		❖ Heat rate was monitored and targeted at >85% of maximum heart rate.		• Fitness level (BMI, BFM): positive effect.
10	Memarmoghaddam et al., 2016	Iran RCT Research	36 boys with ADHD (aged 7-11 years): 19 in experimental group, 17 in control group.	No	❖ Combined aerobic exercise intervention; 8 weeks; 3x/week; 90 mins/session (including warm-up, goal-directed exercise, station training, cool-down). ❖ The intervention was supervised by trained physical education experts. ❖ Heart rate was monitored during the intervention.	Inactive	• Cognitive function (Stroop test, Go-No-Go test): positive effect*.
11	Pan et al., 2016	Taiwan, China RCT Research	32 boys with ADHD (aged 6-12 years): 16 in intervention group, 16 in control group.	Partially	❖ Table tennis intervention; 12 weeks; 2x/week; 70 mins/session (including warm-up, motor skills practice, executive function training by using table tennis exercise, group games, cool-down). ❖ The intervention was supervised by instructors.	Routine care	• Motor skills (BOT-2): positive effect*; • Behavioral problems (CBCL): positive effect*, • Executive functions (Stroop test): positive effect*.
12	Lee, Lee, & Park 2015	South Korea RCT Research	12 boys with ADHD (mean aged 8.83 years old): 6 in the combined exercise group, 6 in control group	No	❖ Combined exercise program; 12 weeks; 3x/week; 60 mins/session (including warm-up, jump rope combined with ball exercise, cool-down). ❖ Heart rate is monitored during the program.	Inactive	• Fitness level (cardiorespiratory endurance, muscle strength/endurance, flexibility): positive effect*; • Neurotransmitters (epinephrine, serotonin): positive effect.
13	Taft Yazd et al., 2015	Iran RCT Research	36 children with ADHD (6-12 years old, 30 boys and 6 girls, 12 per arm)	Yes	❖ Motor-perceptual training with medication (CMOT), Motor-perceptual training only (MOT): 6 weeks, 3x/week, NA data for min/session. Medication was used the same regimen as DRUG group.	Daily medication (DRUG): methylphenidate (<10 mg) and risperidone (0.5-1 mg).	• Motor-skills (BOTMP): Positive effect* in both MOT and CMOT group.
14	Kosari et al., 2013	Iran Quasi-experimental design School	20 boys with ADHD (aged 8.8 years old): 10 in experimental group and 10 in control group	NA	❖ SPARK physical education program; 18 sessions; 45 mins/session (including warm-up, motor displacement activities, manipulative motor skills, cool-down). ❖ The program was instructed by skilled physical trainers.	Routine care	• Gross motor skills (BOTMP): positive effect*.
15	Verret et al., 2012	Canada Quasi-experimental design School	21 children with ADHD (aged 7-12 years old): 10 in training program, 8 in control group	Yes	❖ The training program; 10 weeks; 3x/week; 45 mins/session (including warm-up, progressive aerobic, muscular, and motor skills exercises, cool down). ❖ The program was supervised by a physical activity specialist.	NA	• Behavioral problems (CBCL): positive effect*; • Fitness level (fitness tests): positive effect; • Cognitive functioning (Sky search test): positive effect.
16	Ahmed & Mohamed, 2011	Saudi Arabic RCT School and home	84 adolescents with ADHD (54 boys and 30 girls, 11-16 years old): 42 in experimental group, 42 in control group.	NA	❖ Aerobic exercise program; 10 weeks; 3x/week; 40-50 mins/session (including warm-up, aerobic exercise, walking, cool-down). ❖ The program was instructed by research team.	Inactive	• Behavioral, cognitive and psychological response (parent/teacher rated Behavior Rating Scale): positive effect*.
Single-bout of SPE							
17	Hung et al., 2016	Taiwan, China Quasi-experimental design (Study 2) Research	34 children with ADHD (mean aged 10.16 years old, 33 boys and 1 girl): 17 in experimental group, 17 in control group.	Partially	❖ Single bout moderate-intensity aerobic exercise session; 30 mins (including warm-up, treadmill exercise, cool-down). ❖ Heart rate was monitored during the exercise.	Video-watching while seated	• Working memory (Task switching): positive effect.
18	Chang et al., 2012	Taiwan, China RCT Research	40 children with ADHD (aged 8-13 years old, 37 boys and 3 girls):	Partially	❖ Single bout moderate-intensity aerobic exercise session; 30 mins (including warm-up, treadmill exercise, cool-down). ❖ Heart rate was monitored during the exercise.	Video-watching while seated	• Response inhibition (Stroop test): positive effect*; • Cognitive processing (WCST): positive effect*.

* Statistically significant.

Table 4. Summarized results of meta-analyses.

Group/subgroup	k	Effect size, heterogeneity and subgroup analysis: SMD [a]	95% CI	I^2	$P_{subgroup}$	Publication bias by Egger's test: Beta 1 (SE)	z	*P or* adjusted *P*	Estimation by trim-and-fill method: Inputted studies (n, location of input)	Adjusted SMD [95% CI]
Primary Outcomes										
1. ADHD symptomology										
1.1 Overall ADHD symptoms	4	-0.97	[-2.26, 0.32]	92%***		-24.64 (13.22)	-1.86	0.062	-	-
Program design					<0.001					
Perceptual training	1	-3.23	[-4.09, -2.37] ***	-						
No perceptual training	3	-0.27	[-0.66, 0.13]	0%						
1.2 Inattention	4	-1.79	[-3.28, -0.30] *	88%***		-8.15 (1.52)	-5.38	<0.001	1 (right)	-1.37 [-3.09, 0.36]
Study quality					<0.001	10.81 (26.97)	0.40	0.689		
High	2	-0.40	[-0.91, 0.11]	0%						
Low	2	-3.56	[-4.69, -2.42] ***	0%						
2. Executive function	**15**	**2.19**	**[1.41, 2.98] *****	**92%*****						
2.1 Cognitive flexibility	4	2.24	[0.03, 4.45]	96%***		9.97 (4.60)	2.17	0.030	0	-
Ethnicity of participants					<0.001	0.01 (6.74)	0.00	0.999		
Chinese	2	0.36	[-0.98, 1.70]	86%**						
Non-Chinese	2	4.33	[3.44, 5.23] ***	0%						
Program design					0.008	7.02 (7.01)	1.00	0.317		
Single bout of SPE	1	-0.30	[-0.93, 0.32]	-						
Long-term practice	3	3.13	[0.67, 5.59] *	93%***						
2.2 Response inhibition	4	1.99	[1.34, 2.63] ***	60%		7.18 (5.31)	1.35	0.177	-	-
2.3 Selective attention	4	1.70	[0.56, 2.85] **	84%***		5.28 (1.17)	4.50	<0.001	1 (left)	1.36 [0.31, 2.41]
Methylphenidate use					<0.001	10.12 (6.80)	1.49	0.136		
Yes	3	2.14	[1.48, 2.80] ***	0%						
Not sure	1	0.50	[0.06, 0.93] *	-						
2.4 Memory function	3	3.14	[-0.35, 6.64]	97%***		17.47 (4.67)	3.74	<0.001	0	-
Program design					<0.001	0.00 (-)	-	-		
Single bout of SPE	1	0.02	[-0.65, 0.69]	-						
Long-term practice	2	4.70	[3.87, 5.53] ***	0%						
Secondary Outcomes										
3. Body-mass index (BMI)	**6**	**-0.14**	**[-0.48, 0.20]**	**17%**		-0.50 (2.70)	-0.19	0.853	-	-
4. Physical fitness	**15**	**1.36**	**[0.97, 1.75] *****	**67%*****						
4.1 Aerobic capacity	6	1.81	[0.98, 2.64] ***	73%**		4.56 (3.75)	1.22	0.224	-	-
Study quality										
High	2	0.60	[-0.04, 1.24]	0%						
Low	4	2.41	[1.86, 2.95] ***	0%						
4.2 Motor skills	9	1.08	[0.71, 1.45] ***	49%		4.22 (1.18)	3.56	<0.001	2 (left)	0.90 [0.42, 1.37]
Program design					<0.001	2.39 (1.55)	1.54	0.123		
Motor skill training	3	1.91	[1.32, 2.51] ***	0%						
Other focuses	6	0.74	[0.47, 1.02] ***	0%						
5. Mental health issues	**8**	**-0.89**	**[-1.57, -0.21] ***	**76%*****						
5.1 Depression	4	-1.67	[-2.87, -0.47] **	76%***		-8.65 (2.10)	-4.11	<0.001	1 (right)	-1.46 [-2.37, -0.55]
Study quality					<0.001	3.84 (41.96)	0.09	0.927		
High	1	-0.26	[-0.96, 0.44]	-						
Low	3	-2.24	[-2.94, -1.54] ***	0%						
5.2 Anxiety	4	-0.22	[-0.77, 0.32]	37%		0.90 (7.41)	0.12	0.903	-	-

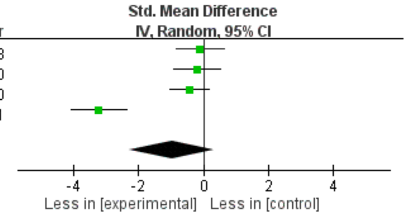
$*p < 0.05$, $**p < 0.01$, $***p < 0.001$. [a] SMD implemented in RevMan 5.4.1 is Hedges' adjusted *g*, which includes an adjustment of small sample bias.

Online supplemental material.

(a) Overall ADHD symptoms

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
Meßler, Holmberg, & Sperlich, 2018	1.36	0.54	14	1.42	0.62	14	25.0%	-0.10 [-0.84, 0.64]	2018
Durgut, Orengul, & Algun, 2020	85	15.61	15	90.06	30.35	15	25.1%	-0.20 [-0.92, 0.51]	2020
Soori et al., 2020	37.96	8.84	26	41.56	7.27	17	25.6%	-0.43 [-1.05, 0.19]	2020
Kouhbanani & Rothenberger, 2021	56	4.8	25	69	2.9	25	24.3%	-3.23 [-4.09, -2.37]	2021
Total (95% CI)			**80**			**71**	**100.0%**	**-0.97 [-2.26, 0.32]**	

Heterogeneity: Tau^2 = 1.60; Chi^2 = 37.96, df = 3 (P < 0.00001); I^2 = 92%
Test for overall effect: Z = 1.47 (P = 0.14)



(b) Inattention

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
Verret et al., 2012	83.3	3.4	9	96	3.4	9	22.1%	-3.56 [-5.16, -1.95]	2012
Pan et al., 2016	9.69	3	16	11.5	4.05	16	28.0%	-0.50 [-1.20, 0.21]	2016
Meßler, Holmberg, & Sperlich, 2018	1.19	0.6	14	1.37	0.6	14	27.8%	-0.29 [-1.04, 0.45]	2018
Ardakani & Ardakani, 2020	83.3	3.4	9	96	3.4	9	22.1%	-3.56 [-5.16, -1.95]	2020
Total (95% CI)			**48**			**48**	**100.0%**	**-1.79 [-3.28, -0.30]**	

Heterogeneity: Tau^2 = 1.94; Chi^2 = 24.82, df = 3 (P < 0.0001); I^2 = 88%
Test for overall effect: Z = 2.36 (P = 0.02)

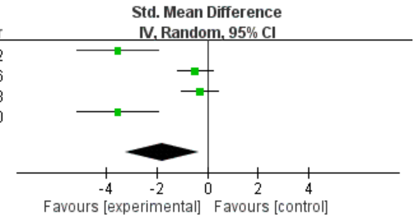


Figure S1. Forest plot of effect of structured physical exercises on ADHD symptomology of children and adolescents with ADHD in terms of (a) overall ADHD symptoms and (b) inattention.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
1 Cognitive flexibility									
Chang et al., 2012	72.85	12.33	20	76.4	10.7	20	7.1%	-0.30 [-0.93, 0.32]	2012
Pan et al., 2019	82.27	10.89	15	72.47	6.45	15	6.9%	1.07 [0.29, 1.84]	2019
Da Silva et al., 2019	109	10	10	69.6	9	10	5.7%	3.97 [2.34, 5.59]	2019
Kouhbanani & Rothenberger, 2021	75.5	13.89	25	18.05	11.12	25	6.5%	4.49 [3.42, 5.57]	2021
Subtotal (95% CI)			**70**			**70**	**26.2%**	**2.24 [0.03, 4.45]**	
Heterogeneity: Tau^2 = 4.80; Chi^2 = 69.72, df = 3 (P < 0.00001); I^2 = 96%									
Test for overall effect: Z = 1.98 (P = 0.05)									
2 Response inhibition									
Pan et al., 2016	32.13	2.92	16	23.44	2.97	16	6.6%	2.88 [1.85, 3.90]	2016
Memarmoghaddam et al., 2016	44.63	1.25	19	42	2.73	17	7.0%	1.24 [0.51, 1.96]	2016
Pan et al., 2019	32.47	2.75	15	24.27	5.47	15	6.8%	1.84 [0.97, 2.72]	2019
Kouhbanani & Rothenberger, 2021	42.3	6.82	25	21.6	11.15	25	7.0%	2.20 [1.49, 2.92]	2021
Subtotal (95% CI)			**75**			**73**	**27.4%**	**1.99 [1.34, 2.63]**	
Heterogeneity: Tau^2 = 0.26; Chi^2 = 7.46, df = 3 (P = 0.06); I^2 = 60%									
Test for overall effect: Z = 6.02 (P < 0.00001)									
3 Selective attention									
Ahmed & Mohamed, 2011	8.46	3.61	42	5.62	7.15	42	7.3%	0.50 [0.06, 0.93]	2011
Verret et al., 2012	7.8	0.8	10	5.4	0.8	11	6.2%	2.88 [1.59, 4.17]	2012
Da Silva et al., 2019	104	9	10	78.2	14	10	6.4%	2.10 [0.96, 3.24]	2019
Ardakani & Ardakani, 2020	6.6	0.5	10	5.4	0.8	11	6.6%	1.71 [0.68, 2.74]	2020
Subtotal (95% CI)			**72**			**74**	**26.5%**	**1.70 [0.56, 2.85]**	
Heterogeneity: Tau^2 = 1.11; Chi^2 = 18.69, df = 3 (P = 0.0003); I^2 = 84%									
Test for overall effect: Z = 2.91 (P = 0.004)									
4 Memory function									
Hung et al., 2016	73.32	13.49	17	73.06	14.58	17	7.1%	0.02 [-0.65, 0.69]	2016
Hattabi et al., 2019	32.45	1.9	20	22.95	1.82	20	6.2%	5.00 [3.69, 6.32]	2019
Kouhbanani & Rothenberger, 2021	75.5	13.89	25	18.05	11.12	25	6.5%	4.49 [3.42, 5.57]	2021
Subtotal (95% CI)			**62**			**62**	**19.8%**	**3.14 [-0.35, 6.64]**	
Heterogeneity: Tau^2 = 9.25; Chi^2 = 74.14, df = 2 (P < 0.00001); I^2 = 97%									
Test for overall effect: Z = 1.76 (P = 0.08)									
Total (95% CI)			**279**			**279**	**100.0%**	**2.19 [1.41, 2.98]**	

Heterogeneity: Tau^2 = 2.18; Chi^2 = 185.56, df = 14 (P < 0.00001); I^2 = 92%
Test for overall effect: Z = 5.45 (P < 0.00001)

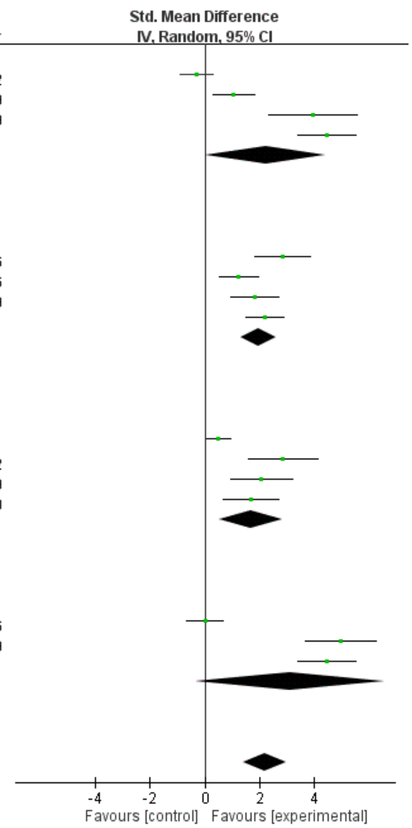


Figure S2. Forest plot of effect of structured physical exercises on executive functions of children and adolescents with ADHD.

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
Verret et al., 2012	17.5	0.6	10	17.3	0.6	8	11.7%	0.32 [-0.62, 1.25]	2012
Torabi et al., 2018 (female participants)	25.4	2.1	15	26.1	3.2	15	18.4%	-0.25 [-0.97, 0.47]	2018
Torabi et al., 2018 (male participants)	23.6	3.8	10	27.1	2	10	11.3%	-1.10 [-2.06, -0.15]	2018
Hattabi et al., 2019	18.03	2.24	20	18.05	2.29	20	23.2%	-0.01 [-0.63, 0.61]	2019
Ardakani & Ardakani, 2020	17.5	0.6	10	17.3	0.6	8	11.7%	0.32 [-0.62, 1.25]	2020
Soori et al., 2020	1.43	0.66	26	1.52	0.26	17	23.7%	-0.16 [-0.78, 0.45]	2020
Total (95% CI)			**91**			**78**	**100.0%**	**-0.14 [-0.48, 0.20]**	
Heterogeneity: Tau² = 0.03; Chi² = 6.01, df = 5 (P = 0.31); I² = 17%									
Test for overall effect: Z = 0.79 (P = 0.43)									

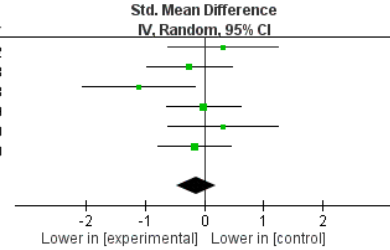


Figure S3. Forest plot of effect of structured physical exercises on BMI of children and adolescents with ADHD.

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
1 Aerobic capacity									
Verret et al., 2012	17.8	2.1	10	12.1	2.5	8	5.0%	2.38 [1.10, 3.66]	2012
Lee, Lee, & Park, 2015	71.27	8.35	6	63.72	7.08	6	5.3%	0.90 [-0.31, 2.11]	2015
Meßler, Holmberg, & Sperlich, 2018	100	16	14	94	6	14	7.7%	0.48 [-0.27, 1.24]	2018
Hattabi et al., 2019	42.09	2.37	20	36.84	2.08	20	7.3%	2.31 [1.49, 3.12]	2019
Da Silva et al., 2019	38	3	10	28	4	10	5.0%	2.71 [1.43, 3.99]	2019
Ardakani & Ardakani, 2020	17.8	2.1	10	12.1	2.5	8	5.0%	2.38 [1.10, 3.66]	2020
Subtotal (95% CI)			**70**			**66**	**35.2%**	**1.81 [0.98, 2.64]**	
Heterogeneity: Tau² = 0.76; Chi² = 18.29, df = 5 (P = 0.003); I² = 73%									
Test for overall effect: Z = 4.27 (P < 0.0001)									
2 Motor skills									
Ahmed & Mohamed, 2011	7.97	3.96	42	4.95	6.07	42	9.5%	0.58 [0.15, 1.02]	2011
Kosari et al., 2013	23.9	2.46	10	18.4	1.5	10	5.1%	2.59 [1.33, 3.84]	2013
Taft Yazd et al., 2015 (CMOT vs DRUG)	49.5	9.95	12	32.08	9.67	12	6.5%	1.71 [0.75, 2.67]	2015
Taft Yazd et al., 2015 (MOT vs DRUG)	52.1	12.63	12	32.08	9.67	12	6.5%	1.72 [0.76, 2.68]	2015
Pan et al., 2016	64.13	9.5	16	55.88	10.74	16	7.8%	0.79 [0.07, 1.52]	2016
Torabi et al., 2018 (male participants)	41.8	9.5	10	30.9	6.6	10	6.4%	1.28 [0.29, 2.26]	2018
Meßler, Holmberg, & Sperlich, 2018	11.1	2.5	14	8.7	3.8	14	7.6%	0.72 [-0.04, 1.49]	2018
Torabi et al., 2018 (female participants)	42.1	9.3	15	37.2	4.7	15	7.8%	0.65 [-0.09, 1.38]	2018
Pan et al., 2019	43.33	2.5	15	40	4.02	15	7.6%	0.97 [0.21, 1.73]	2019
Subtotal (95% CI)			**146**			**146**	**64.8%**	**1.08 [0.71, 1.45]**	
Heterogeneity: Tau² = 0.15; Chi² = 15.73, df = 8 (P = 0.05); I² = 49%									
Test for overall effect: Z = 5.71 (P < 0.00001)									
Total (95% CI)			**216**			**212**	**100.0%**	**1.36 [0.97, 1.75]**	
Heterogeneity: Tau² = 0.37; Chi² = 41.94, df = 14 (P = 0.0001); I² = 67%									
Test for overall effect: Z = 6.82 (P < 0.00001)									

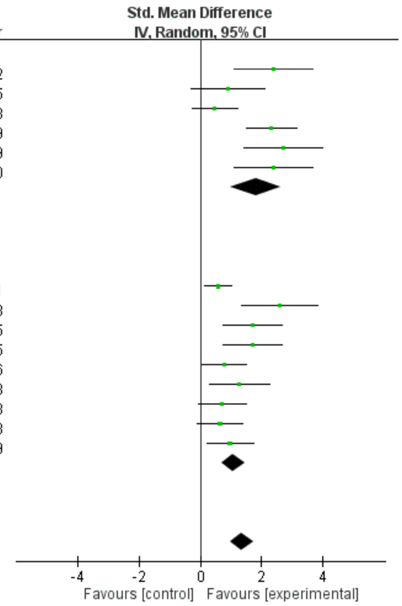


Figure S4. Forest plot of effect of structured physical exercises on physical fitness of children and adolescents with ADHD.

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
1 Depression									
Verret et al., 2012	79.9	3.1	9	87.2	3.1	9	10.8%	-2.24 [-3.48, -1.00]	2012
Pan et al., 2016	3	2.39	16	3.63	2.31	16	14.3%	-0.26 [-0.96, 0.44]	2016
Da Silva et al., 2019	10.2	2	10	16.4	3	10	11.1%	-2.33 [-3.52, -1.14]	2019
Ardakani & Ardakani, 2020	79.9	3.1	9	87.2	3.4	9	11.0%	-2.14 [-3.35, -0.92]	2020
Subtotal (95% CI)			**44**			**44**	**47.2%**	**-1.67 [-2.87, -0.47]**	
Heterogeneity: Tau² = 1.19; Chi² = 15.40, df = 3 (P = 0.002); I² = 81%									
Test for overall effect: Z = 2.73 (P = 0.006)									
2 Anxiety									
Verret et al., 2012	71.4	21.6	9	82.8	17.5	9	12.7%	-0.55 [-1.50, 0.39]	2012
Pan et al., 2016	5.63	5.28	16	7.5	3.65	16	14.3%	-0.40 [-1.10, 0.30]	2016
Da Silva et al., 2019	15.7	3	10	13.3	4	10	13.0%	0.65 [-0.25, 1.56]	2019
Ardakani & Ardakani, 2020	71.4	21.6	9	82.8	17.5	9	12.7%	-0.55 [-1.50, 0.39]	2020
Subtotal (95% CI)			**44**			**44**	**52.8%**	**-0.22 [-0.77, 0.32]**	
Heterogeneity: Tau² = 0.11; Chi² = 4.76, df = 3 (P = 0.19); I² = 37%									
Test for overall effect: Z = 0.79 (P = 0.43)									
Total (95% CI)			**88**			**88**	**100.0%**	**-0.89 [-1.57, -0.21]**	
Heterogeneity: Tau² = 0.72; Chi² = 29.40, df = 7 (P = 0.0001); I² = 76%									
Test for overall effect: Z = 2.55 (P = 0.01)									

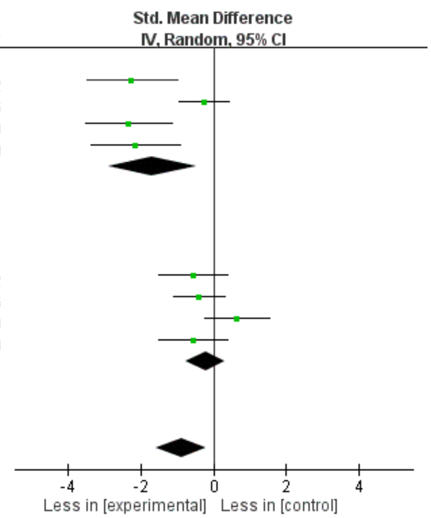


Figure S5. Forest plot of effect of structured physical exercises on mental health issues of children and adolescents with ADHD.

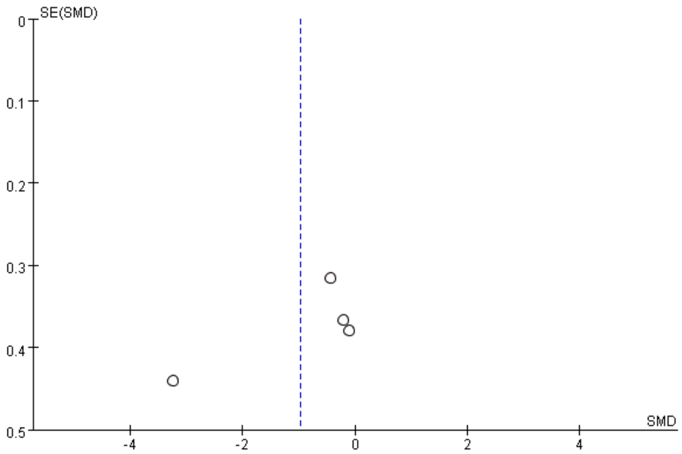


Figure S6. Funnel plot representing publication bias of studies analyzed for overall ADHD symptoms.

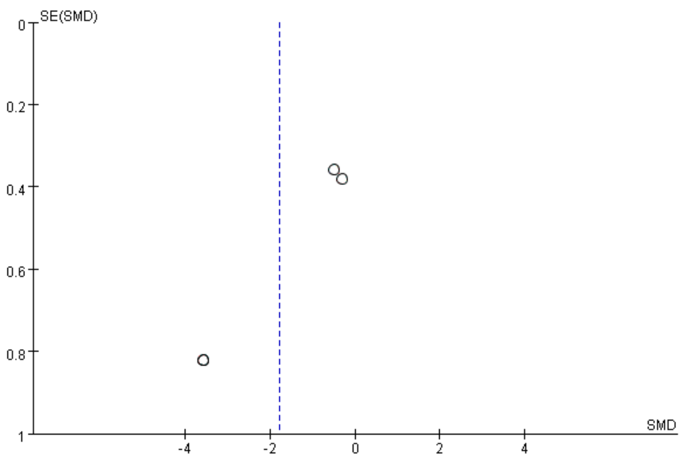


Figure S7. Funnel plot representing publication bias of studies analyzed for inattention.

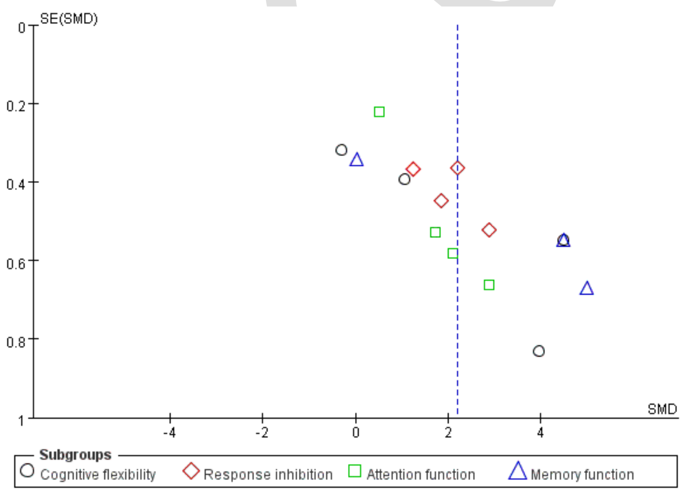


Figure S8. Funnel plot representing publication bias of studies analyzed for executive function.

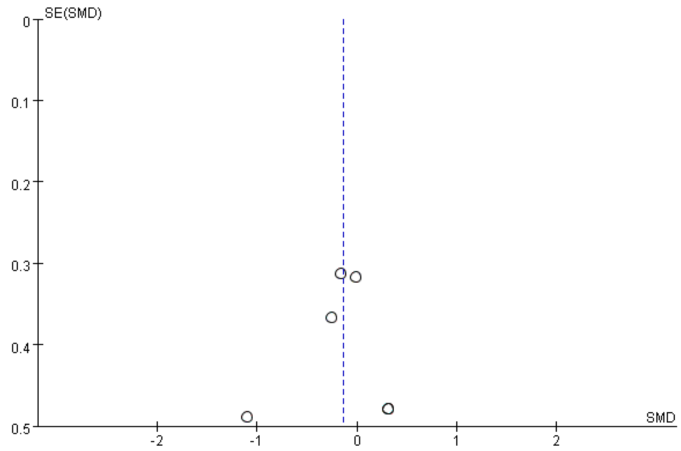


Figure S9. Funnel plot representing publication bias of studies analyzed for BMI.

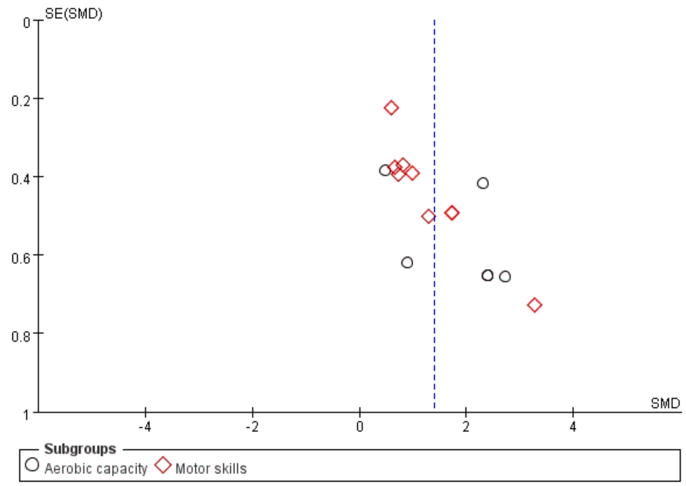


Figure S10. Funnel plot representing publication bias of studies analyzed for physical fitness.

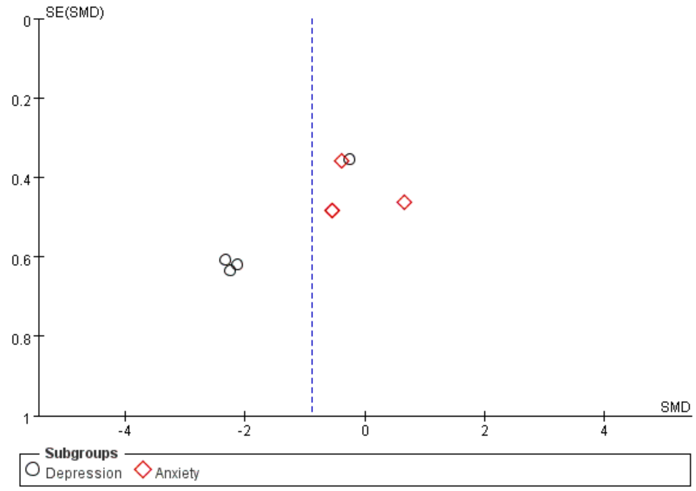


Figure S11. Funnel plot representing publication bias of studies analyzed for mental health issues.