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Effects of a single bout of moderate-to-vigorous physical activity on executive functions in children with attention-deficit/hyperactivity disorder: A systematic review and meta-analysis

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ABSTRACT

Objectives: The aim of this study was to systematically review the literature investigating the acute effects of moderate-to-vigorous physical activity (MVPA) on executive functions (EFs) in children with attention-deficit/hyperactivity disorder (ADHD) and perform a meta-analysis of the effects of MVPA on task components that require lower and higher EF demand in this population.
Methods: The systematic review and meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. Six electronic databases, i.e., PubMed, Scopus, Web of Science, Embase, SPORTDiscus, and Education Resources Information Center (ERIC), were searched for eligible studies. Random-effects weights were used to pool the effect sizes. Publication bias was assessed by Egger's regression test and Rosenthal's fail-safe *N*. This study is registered on PROSPERO, number CRD42020184082.
Results: The electronic database search yielded 12 studies, which met the inclusion criteria, comprising a total of 375 participants. Eleven studies with data from 275 participants were included in the meta-analysis to examine the acute effects of MVPA on tasks with lower and higher EF demand. A single bout of MVPA had a small positive effect on tasks with lower ($n = 10$, $g = 0.32$, 95% CI = 0.123–0.517) and higher ($n = 10$, $g = 0.25$, 95% CI = 0.13–0.371) EF demand. No publication bias was found.
Conclusions: A single bout of MVPA may have a general facilitative effect on cognition, indicating that acute MVPA may be a transient nonpharmacological adjunctive treatment for childhood ADHD.

1. Introduction

Attention-deficit/hyperactivity disorder (ADHD) is one of the most common psychiatric disorders in school-aged children and is characterized by a developmentally inappropriate pattern of inattention, impulsiveness, and/or hyperactivity (American Psychiatric Association, 2013). The global prevalence of ADHD in school-aged children is around 7.2% (Thomas et al., 2015) and 60% of children diagnosed with ADHD have symptoms that persist into adulthood (Sibley et al., 2017). Although the pathophysiology of ADHD is complicated, including hypoarousal (Bellato et al., 2020; Saad et al., 2018), dysfunction in specific neural circuits (e.g., frontoparietal, dorsal, and ventral attentional networks) (Castellanos & Proal, 2012), and imbalanced catecholamine neurotransmission (Arnsten & Pliszka, 2011), all these neurophysiological disturbances contribute to neurocognitive deficits in executive functions (EFs).

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Broadly defined, EFs refer to a collection of top-down processes that employ inhibitory control (also called executive attention, i.e., focusing on stimuli while suppressing irrelevant information or inhibiting prepotent mental representations or response tendency), working memory (holding and mentally organizing information), and cognitive flexibility (flexibly adjusting behavior or thoughts based on updated demands, rules, or priorities) to carry out goal-directed behaviors (Diamond, 2013; Miller & Cohen, 2001; Miyake et al., 2000; Zelazo, 2015) and higher-level cognitive operations, such as motor planning and problem solving (Collins & Koechlin, 2012; Lunt et al., 2012). Children with ADHD also exhibit cognitive impairment in lower EF processing. Previous studies have reported that compared with typically developing control subjects, children with ADHD exhibit poor performance in cognitive tasks regardless of the tasks' EF demands (e.g., congruent vs. incongruent flanker tasks, homogenous vs. heterogeneous task switching) (Hung et al., 2016; Ludyga et al., 2017; Pontifex et al., 2013). Low EF demand conditions require less EF involvement than high EF demand conditions. A recent review study indicated that both low (selective or sustained attention) and high EF demand (three core EF components: inhibitory control, working memory, and cognitive flexibility) in cognitive functioning are important for behavior management and learning efficacy in ADHD (Mueller et al., 2017). Psychostimulant medications have generally been used to transiently mitigate these cognitive deficits associated with ADHD (Mueller et al., 2017; Wolraich et al., 2019). However, the potential risk of adverse effects from medication, such as insomnia, lack of appetite, headache, and decreased growth velocity (Newcorn et al., 2010; Swanson et al., 2007), sometimes leads to poor adherence (Adler & Nierenberg, 2010; Kovshoff et al., 2012). Thus, it is necessary to find a treatment option with minimal adverse effects in children with ADHD to temporarily improve their EFs regardless of the EF demand. Acute moderate-to-vigorous physical activity (MVPA) could be a good candidate for children with ADHD.

Regularly engaging in MVPA is an effective means of promoting health-related outcomes in school-aged children, such as physical fitness, cardiometabolic health, and bone health (Bull et al., 2020). Importantly, the 2018 Physical Activity Guidelines for Americans also indicated that MVPA is an effective means of transiently facilitating cognition during the post-exercise period (Erickson et al., 2019). Studies have reported more cognitive benefits resulting from acute MVPA than acute light-intensity exercise in healthy populations (Bailey et al., 2021; Zimmer et al., 2016). One proposed mechanism is that acute bouts of MVPA improve cognition as a result of modulations in the locus coeruleus (LC)–norepinephrine (NE) system (Pontifex et al., 2019). This pathway for cognitive enhancement following acute bouts of MVPA may correspond to the use of psychostimulant medication (i.e., methylphenidate) in ADHD (Berridge & Spencer, 2016). Both human studies and animal models have suggested that the activation of the LC and the associated release of NE play an important role in the regulation of the prefrontal-dependent aspect of cognition (Aston-Jones & Cohen, 2005; Poe et al., 2020). Based on microinjection experiments, optimal cognitive performance may occur under a sufficient level of NE release (Aston-Jones & Cohen, 2005). Despite the strong neurophysiological basis for adopting MVPA as an adjunctive treatment for temporarily improving cognitive performance in ADHD, a firm conclusion has not yet been obtained because previous meta-analyses (Liang et al., 2021; Vysniauske et al., 2020) have certain limitations. Specifically, they did not provide precise estimates of the effects of a single bout of MVPA on EFs as they included both chronic and acute PA studies or omitted important relevant studies (e.g., Ludyga et al., 2017; Piepmeier et al., 2015; Yu et al., 2020), and they did not examine possible moderators, such as the EF demand associated with the EF tasks. Therefore, it is necessary to exclusively focus on studies that have implemented acute MVPA and targeted EFs to assess the effects of a single bout of MVPA more precisely.

Moreover, whether acute bouts of MVPA yield a general or selective effect on tasks with different EF demands in children with ADHD remains controversial. For example, while a few studies found that a single bout of MVPA only benefits cognitive tasks with higher EF demand in children with ADHD (Benzing et al., 2018; Chang et al., 2012; Hung et al., 2016), other studies indicated that it resulted in a global facilitative effect on cognition regardless of EF demand (Ludyga et al., 2017; Pontifex et al., 2013; Yu et al., 2020). As such, the present systematic review and meta-analysis aimed to synthesize the effects of a single bout of MVPA on EFs in children with ADHD, with a particular focus on task components with lower and higher EF demands. Our findings could be helpful in formulating a specific acute exercise prescription for transiently facilitating EFs in children with ADHD.

2. Methods

The study protocol for this systematic review and meta-analysis was registered at PROSPERO (International Prospective Register of Systematic Reviews) with the registration number (CRD42020184082) and complied with the PRISMA guidelines (Page et al., 2021).

2.1. Eligibility criteria

The inclusion criteria for articles in this review were developed using the Population, Intervention, Comparison, Outcome and Study (PICOS) framework (Moher et al., 2015). The inclusion criteria were as follows: (P) the participants included the studies were school-aged children (6–17 years old) diagnosed with ADHD; (I) the studies used intervention designs to evaluate the effects of a single bout of MVPA on EFs. MVPA was defined as a relative intensity of 64–95% of the individualized maximal heart rate (HR_{max}), 40–89% of the heart rate reserve (HRR), and 46–90% of the maximal oxygen consumption (VO_2max) (Garber et al., 2011). If the studies did not use the above conventional methods or report the specific criteria for physical activity (PA) intensity, we calculated the mean HR during PA periods extracted from the studies and estimated HR_{max} using formula 208–0.7 × (age) (Mahon et al., 2010) to determine the PA intensity; (C) the studies included non-exercise or active control condition/group; (O) the studies incorporated neuropsychological tests to evaluate the main neurocognitive deficits in ADHD, such as low EF processing (selective or sustained attention) or three EF core components[1] (i.e., inhibitory control, working memory or cognitiveflexibility) (Mueller et al., 2017); and (S) the studies included crossover or parallel group comparison trials.[2]

2.2. Information sources and search strategy

Six electronic databases were used, namely, PubMed, Scopus, Web of Science, Embase, SPORTDiscus (EBSCOhost), and ERIC (OvidSP). All identified articles published prior to December 2020 were included. The literature search was updated to identify eligible published articles from January to July 2021. Search keywords were defined by the research team and used in each database to identify potential articles for review. Medical subject headings (MeSH) were utilized when searching in PubMed. The analysis was restricted to English language and original research articles published in peer-reviewed journals. The full search terms for all databases are provided in Supplementary Appendix S1.

[1] EF components may depend on different EF models. We included three EF components (i.e., inhibitory control, working memory, and cognitive flexibility), which are consistently reported to be core EF components regardless of the model used (Diamond, 2013; Miyake et al., 2000; Zelazo, 2015).

[2] Few studies have explored the acute effects of PA on EFs in children with ADHD; thus, studies using randomized control trials (RCTs) and non-RCTs were included.

2.3. Selection process

The articles for inclusion in the review were decided with reference to the PICOS criteria. Titles/abstracts were independently assessed for eligibility by two authors (TYC and CLY). A full-text article review was performed by three authors (TYC, YJT and VB). A Microsoft Excel spreadsheet was developed to track eligibility status. Decisions to include or exclude studies were made by consensus. Any disputes were settled by discussion with other author of this study (TMH). In addition to the database search, the reference lists of all included studies were checked to identify additional eligible articles (Horsley et al., 2011).

2.4. Data collection process and items

Three authors independently conducted the data extraction (TYC, SHH, and CLY). Disagreements were discussed until a consensus was reached. The extracted information from eligible articles included study information (first author's name, publication year, and region), participant description (sample size, age, sex, and medication intake), study design, intervention protocol (i.e., type, intensity, and duration), comparators (i.e., nonexercise condition/group), and outcomes.

The accuracy or time-dependent measures were the main outcomes in the current study. Acute exercise-related improvements in cognition that manifest within time-dependent or accuracy outcomes may be dependent upon the task parameters or instructions (Pontifex et al., 2019); thus, the primary outcome (accuracy or time-dependent outcomes) was defined individually by each study. That is, if studies concurrently assessed the accuracy and time-dependent measures for the same cognitive domains, the primary outcome (accuracy or time-dependent outcomes) that was more sensitive to acute exercise was extracted from those individual studies.

Most studies assessed postexercise EF within 30 min after exercise cessation. As such, if a study collected data at more than one postexercise measurement point (e.g., 30 and 60 min postexercise), we only included time points that were deemed highly comparable to those in other studies. In addition, when studies employed two intervention arms, we included the condition whose type and intensity range, indexed as mean HR during exercise, were comparable to that in the other studies (Higgins et al., 2019).

Given that EF tasks commonly consist of two conditions, outcomes were classified into either low EF-demand components (e.g., congruent conditions of the flanker and Stroop tasks, homogenous condition of task switching, or part A of Trail Making Test conditions) or high EF-demand components (e.g., incongruent conditions of the flanker and Stroop tasks, heterogeneous condition of task switching, or part B of Trail Making Test conditions) based on their "task condition effects." Individuals usually demonstrated better performance on tasks with low EF demand than on those with high EF demand. If studies did not report these data or assessed only one task condition, the EF demand was determined by previous studies that used similar cognitive task paradigms or by the research team.

2.5. Study risk of bias assessment

The quality of the studies included in the review was assessed using the Physiotherapy Evidence Database (PEDro) scale (de Morton, 2009). This rating scheme has been demonstrated to be a reliable and valid assessment tool (de Morton, 2009; Foley et al., 2006). Several previous reviews investigating the benefits of acute exercise also applied this scale for assessment of methodological quality (Ishihara et al., 2021; Ludyga et al., 2016; Wilke et al., 2019). The original version of the PEDro scale was modified to more accurately match the intended research purposes of studies on exercise to better fulfill the exercise studies. That is, blinding of participants and experimenters (therapists) are not considered for quality assessment for studies with exercise intervention settings because true blinding could not be accomplished. In addition, item 1 (eligibility criteria and source) is related to external validity or generalizability and therefore is not included when calculating the PEDro score (de Morton, 2009). In summary, 8 items were used to assess the internal validity of the included studies, including random allocation, concealed allocation, baseline comparability, reporting and control of exercise loads, blinded assessors, incomplete outcome data, intervention as allocated, between-group condition analysis, and point estimates and variability. The PEDro ratings were independently calculated by two authors (TYC, and YJT) who had undergone the PEDro training program.

2.6. Effect measures

The effect size (standardized mean difference, SMD) was calculated individually for each study. To avoid any upwardly biased estimation due to their small sample size (Hedges, 1981), SMD was transformed into the bias-corrected Hedges' g by multiplying SMD by the correction factor J $(J = 1 - [3/(4df - 1)])$. Due to differences in data dependency between a parallel-group design(between-subjects) and a crossover design (within-subjects), different equations were used to compute Hedges' g and variance for these different designs (Sloan et al., 2021). For parallel groups design, the effect size was calculated from the difference in mean gain scores between pre-to postexercise treatments and pre-to postcontrol groups, and was standardized by an estimate of the pooled standard deviation (SD) change using the formula $\sqrt{(n1-1)\Delta SD1^2 + (n2-1)\Delta SD2^2/n1 + n2 - 2}$. The variance was computed using the formula $n1 + n2/n1n2 + SMD^2/2(n1 + n2)$ (Borenstein et al., 2009). For crossover studies, the effect size was obtained from the difference in mean gain scores between pre-to postexercise treatments and pre-to postcontrol conditions, and was standardized by an estimate of the mean difference (MD) of standard error (SE) using the formula $SE\,(MD) \times \sqrt{N/2(1 - Corr}$. The variance was computed using the formula $(1/N + SMD^2/2N) \times 2(1 - Corr)$(Higgins et al., 2019). If studies conducted crossover posttest trials, the effect sizes were calculated from the outcome data following exercise and control conditions. The correlation (*Corr*) is required when computing SD changes within groups. If this value was not presented in these studies, the correlation was conservatively set at 0.5 (Follmann et al., 1992). Effect size values of 0.2, 0.5, and 0.8 represent small, moderate, and large effects, respectively (Cohen, 1988). To reduce the risk of overestimating the precision of the findings and control for independence between studies, the effect sizes for multiple outcomes for different cognitive measurements (e.g., word and color conditions of the Stroop task) were averaged using a formula from Borenstein et al. (2009). All data were extracted from the articles, and if there was insufficient information to calculate the effect size, the authors were contacted to request for the missing information.

2.7. Synthesis methods

The narrative overview provided in the text and Table 1 summarizes the study characteristics of all eligible studies. Comprehensive Meta-Analysis software was used to calculate the summary estimates for the acute effects of PA on different EF demands when enough studies were included (≥5) (Jackson & Turner, 2017). Given the heterogeneity of EF assessments (i.e., task parameters and tools), participants' status (i.e., medication intake), and study designs (i.e., parallel-group and crossover designs) in the included studies, we used a random-effects model (Serghiou & Goodman, 2019; Tufanaru et al., 2015). The evidence of heterogeneity was assessed using a Cochran's Q with a significance level of <0.05 (based on chi-square distribution), and I^2 values were used to judge the degree of heterogeneity. I^2 values of 25%, 50%, and 75% indicate small, medium, and large heterogeneity, respectively (Higgins et al., 2019). Considering that the medication intake may affect the effects of acute exercise on EF, a meta-regression analysis was conducted for the percentage of medication use to examine this potential

Table 1
Summary characteristics of the included studies.

Study		Participant description				Study description		Intervention protocols			Control group/ condition	Outcomes
Author	Region	Sample size	Girls	Mean age (years) (*SD* or range)	Medication intake (%)	Design	*N* of group or conditions	Type	Intensity	Duration (minutes)		
Yu et al. (2020)	Asia	24	1	9.9 (8–12)	33%	2	2	AE	1 (60–70% HRR)	30	Rest (video-watching)	Flanker (low & high EF demand)
*Miklós et al. (2020)	Europe	100	8	8.26–9.7 (6–12)	50%	1	2	AE	2 (60–80% HR_{max})	20	Rest (video-watching)	KiTAP (low & high EF demand)
Suarez-Manzano et al. (2018)	Europe	21	6	11.98 (3.07)	71%	3	2	AE (HIIT)	2 (>85% HR_{max})	20	Rest (video-watching)	D2 (low EF demand)
Benzing et al. (2018)	Europe	46	8	10.48 (8–12)	78.3%	1	2	Exergaming	2 (55–90% HR_{max})	15	Rest (watch a documentary report)	Flanker (low & high EF demand) Color Span Backwards (high EF demand)
Ludyga et al. (2018)	Europe	16	5	12.8 (1.8)	100%	2	2	AE	1 (65–70% HR_{max})	20	Rest (video-watching)	Alternative Uses Task (high EF demand)
#Ludyga et al. (2017)	Europe	16	5	12.8 (1.8)	100%	3	3	AE	1 (65–70% of the HR_{max}, AE)	20	Rest (video-watching)	Flanker (low & high EF demand)
Hung et al. (2016)	Asia	34	1	10.1 (8–12)	41%	2	2	AE	1 (50–70% HRR)	30	Rest (video-watching)	Task switching (low & high EF demand)
Chuang et al. (2015)	Asia	19	3	9.4 (8–12)	47%	2	2	AE	1 (60% HRR)	20	Rest (video-watching)	Go/No Go (low & high EF demand)
Piepmeier et al. (2015)	North America	14	5	10.1 (1.96)	64%	2	2	AE	1 (5–7 OMNI-RPE) $HR_{mean} = 147$	30	Rest (watch a documentary report)	Stroop (low & high EF demand) TMT (low & high EF demand)
Pontifex et al. (2013)	North America	20	6	9.5 (8–10)	0%	2	2	AE	1 (65–75% HR_{max})	20	Rest (seated reading)	Flanker (low & high EF demand)
Chang et al. (2012)	Asia	40	3	10.4 (0.9)	50%	1	2	AE	1 (50%–70% HRR)	30	Rest (video-watching)	Stroop (low & high EF demand) WCST (high EF demand)
Medina et al. (2010)	South America	25	0	9.5 (6–12)	60%	2	2	AE (HIIT)	2 [(HR_{max} − HR LV1) × 0.25 + HR LV1] $HR_{mean} = 167$	30	Stretching	CPT (low & high EF demand)

Note:
1. Study design (1 = a parallel-groups pre/posttest design; 2 = crossover posttest design; 3 = crossover pre/posttest design; intensity (1 = moderate; 2 = moderate to vigorous); type (AE = aerobic-related exercise; HIIT = high-intensity interval training; Con = control condition/group).
2. LV = ventilatory threshold; WCST = Wisconsin Card Sorting Test; HR = heart rate; HRR = heart rate reserve; RPE = Rating of Perceived Exertion; CPT = Conner's continuous performance test.
3. * = No available data for meta-analysis. # = only included data for the moderate-intensity of aerobic exercise intervention in this study.

moderator. To confirm whether the effects of acute exercise on EFs were affected by a speed–accuracy trade-off, we extracted other outcomes (accuracy or time-dependent measures) from those studies that assessed both accuracy and time-dependent measures to perform the meta-analysis. Statistical significance for all tests was set at a p value < .05.

2.8. Reporting bias assessment

The publication bias was assessed by Rosenthal's fail-safe *N* (Rosenthal, 1979) and Egger's regression test (Egger et al., 1997). In the case of publication bias, the trim and fill procedure was performed (Duval & Tweedie, 2000) to provide an estimate of the effect size after considering the potential bias (Rothstein et al., 2005).

3. Results

3.1. Search selection

Eight hundred fifty-seven studies were initially identified from the electronic databases. Of these, 258 duplicates were removed. The remaining 599 articles were screened for titles and abstracts. After the first stage of screening, 27 articles were selected for full-text screening. Of these, 12 studies met the eligibility criteria and were included in the review. Eleven studies were entered into the following quantitative synthesis because of unavailable data from one study (Miklós et al., 2020). The indicated funding for the individual studies did not raise any suspicion. Fig. 1 presents a flow diagram of the literature search.

3.2. Study characteristics and narrative synthesis

Table 1 summarizes the study characteristics. The literature search yielded 12 studies published between 2010 and 2020. The majority of the studies (92%, $n = 11$) employed an aerobic-based PA, such as moderate-intensity continuous treadmill walking/cycling ($n = 8$), moderate-to-vigorous intensity interval cycling ($n = 2$) (Medina et al., 2010; Miklós et al., 2020), and high-intensity interval exercise ($n = 1$) (Suarez-Manzano et al., 2018), while the remaining study employed an aerobic and cognitively demanding PA (i.e., exergaming) (Benzing et al., 2018). All studies utilized a duration between 15 and 30 min per PA bout.

The majority of researchers (83%, $n = 10$) concurrently investigated the acute effects of MVPA on task components requiring lower and higher EF demand. Among the 10 studies, 4 studies (40%) demonstrated the positive effects of MVPA on cognition regardless of the EF demand (Ludyga et al., 2017; Piepmeier et al., 2015; Pontifex et al., 2013; Yu et al., 2020), 3 studies (30%) supported a positive impact of MVPA only on tasks with high EF demand (Benzing et al., 2018; Chang et al., 2012; Hung et al., 2016), and the remaining 3 studies (30%) showed a positive effect only on tasks with low EF demand (Chuang et al., 2015; Medina et al., 2010; Miklós et al., 2020). Two studies assessed tasks with either low (Suarez-Manzano et al., 2018) or high EF demand (Ludyga et al., 2020) and both found a positive effect of acute bouts of MVPA.

3.3. Risk of bias in studies

Fig. 2 summarizes the quality of the included studies. All studies provided key outcome measures for more than 85% of their participants, conducted statistical comparisons, and provided valid measures for at least one key outcome measure of interest. While the majority of studies (66.7%) reported randomly allocating participants in their trials, only one study reported performing a concealed allocation (Benzing et al., 2018), suggesting allocation bias may exist in most of the studies. Some studies (16.7%) reported at least one measure of the severity of the condition being treated and at least one different key outcome measure to confirm the baseline status in different groups (Benzing et al., 2018; Chang et al., 2012). Finally, no study mentioned the blinding of assessors and explicitly stated whether at least one main outcome was included in the statistical analysis (intention-to-treat analysis) of all participants regardless of any subsequent withdrawal from treatment. More detailed information on individual ratings can be found in Supplementary Appendix S2.

3.4. Results of syntheses

Only two studies assessed tasks with either low (Suarez-Manzano et al., 2018) or high EF demand (Ludyga et al., 2020); therefore, we performed a meta-analysis to quantify the effects of single bouts of MVPA on low and high EF tasks based on 10 studies. For tasks with low EF demand, a single bout of MVPA resulted in a small but significant effect ($n = 10$; $g = 0.32$, 95% confidence interval [CI] = 0.123–0.517; $p = .001$), with medium heterogeneity ($Q = 17.797$, $I^2 = 49.43$, $p = .038$). For tasks with high EF demand, a small but positive effect was observed ($n = 10$; $g = 0.25$, 95% CI = 0.130–0.371; $p < .001$), with low heterogeneity ($Q = 7.912$, $I^2 = 0$, $p = .543$). The results of the effects of a single

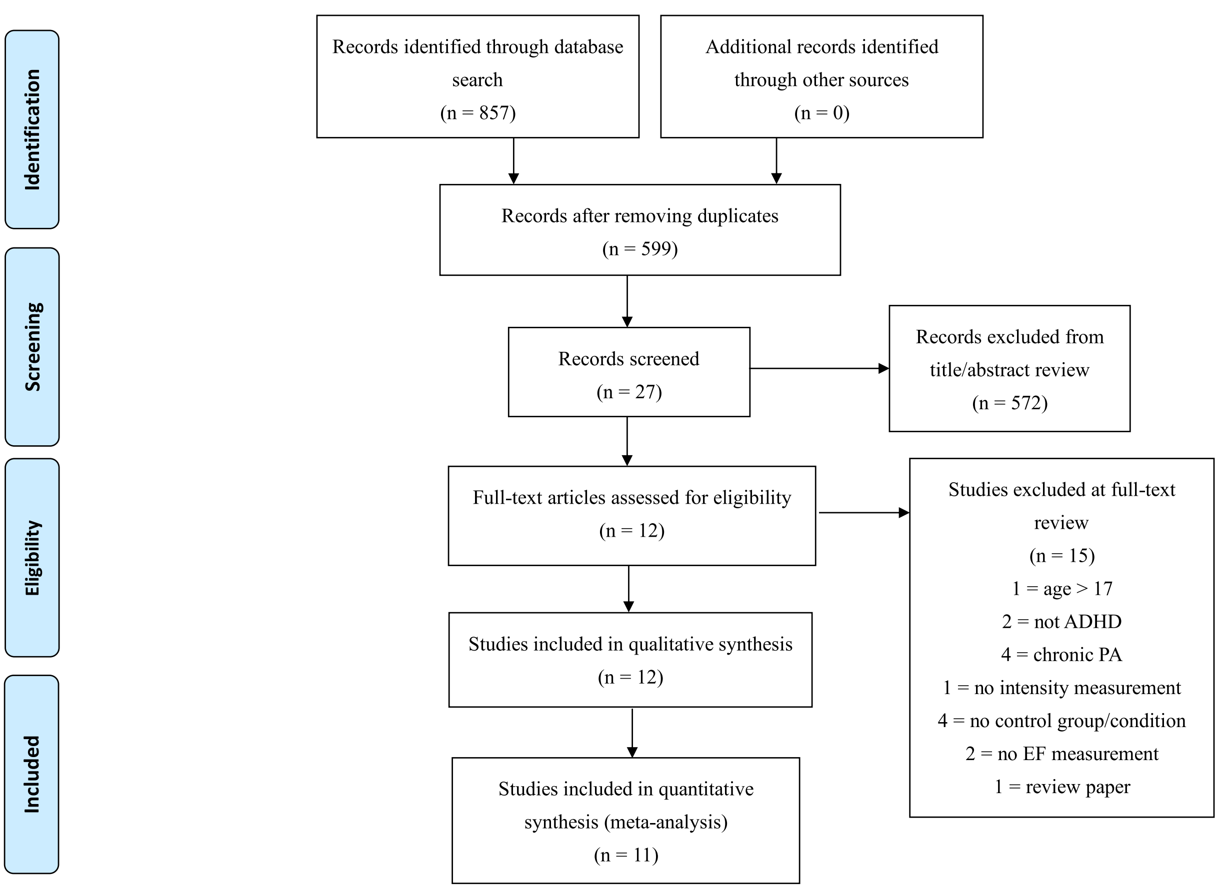

Fig. 1. Search processing.

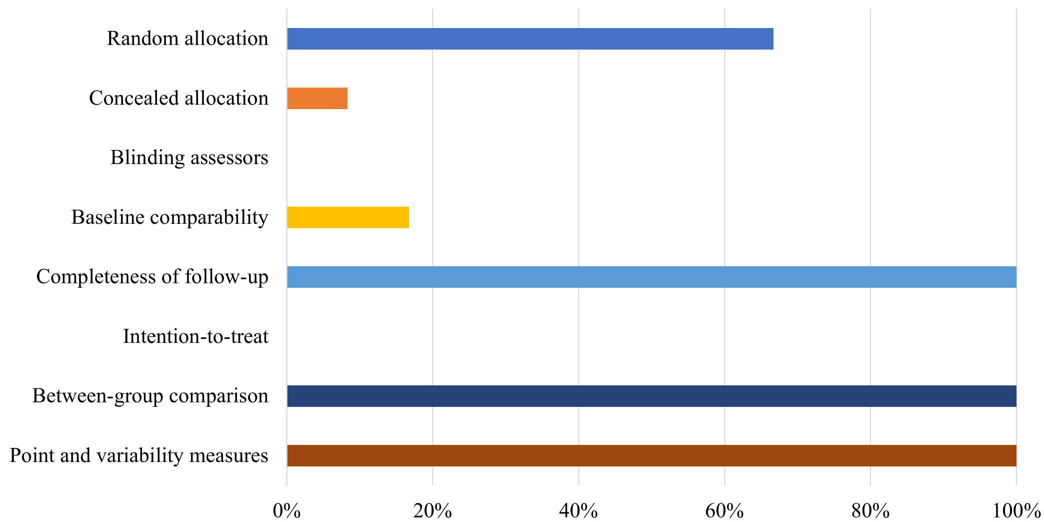

Fig. 2. Study quality overview

bout of MVPA on EF demand are presented in Table 2, and forest plots are presented in Fig. 3.

Meta-regression analyses investigated the moderating effects of medication (i.e., percentage of medication intake). The results showed no evidence of a linear association between the medication use and the magnitude of acute exercise on tasks with low and high EF demand (Q = 0.21, p = .645; Q = 0, p = .951). In addition, no significantly negative effects of acute bouts of MVPA on tasks with low (n = 10, g = 0.03, 95% CI = −0.139–0.198; p = .73) and high (n = 10, g = 0.06, 95% CI = −0.039–0.159; p = .235) EF demand were observed when extracting another outcome from studies using both accuracy and time-dependent measures. That is, the absence of negative effects argues against a simple speed–accuracy trade-off.

As the majority of researchers (75%) used a crossover design (within-subjects) and only three studies (25%) employed a parallel-groups design (between-subjects), we performed secondary analyses to exclusively focus on the within-subject crossover design to obtain meaningful homogeneity across the studies. The results were the same as the primary findings, indicating that a single bout of MVPA resulted in a small but significant effect on tasks with low (n = 8; g = 0.343, 95% CI = 0.111–0.575; p = .004) and high (n = 8; g = 0.222, 95% CI = 0.091–0.353; p = .001) EF demand.

3.5. *Reporting biases*

The results indicated no serious publication bias for all outcomes based on Rosenthal's fail-safe N and Egger's regression test (see Table 2). Thus, the trim-and-fill procedure was not performed.

4. Discussion

This is the first study to summarize the available evidence for the acute effects of MVPA on EFs in children with ADHD. We included 12 studies in this review and extracted the available data from 11 studies for meta-analysis. The results indicate that single bouts of MVPA induce small improvements in tasks with high (g = 0.32) and low (g = 0.25) EF demand. No adverse effects or serious publication bias was observed in our analysis. Overall, the findings indicate that in children with ADHD, a single bout of MVPA has a general facilitative effect on cognition.

The findings of the current study are in line with prior meta-analyses, which found that a single bout of MVPA had positive effects (effect sizes = 0.2–0.54) on EFs in healthy populations (de Greeff et al., 2018; Leahy et al., 2020; Liu et al., 2020; Ludyga et al., 2016). Although previous meta-analyses investigated the effects of acute bouts of PA on EFs in children with ADHD (Liang et al., 2021; Vysniauske et al., 2020), the precise estimates of the magnitude of the effects were inconclusive due to the inclusion of chronic PA studies or omission of several relevant studies (Ludyga et al., 2017; Piepmeier et al., 2015; Yu et al., 2020). In addition, previous studies did not consider the possibility of a speed–accuracy trade-off strategy for only extracting either speed- or accuracy-based measures or the treatment status of the participants. As such, the current study extended the knowledge base by 1) providing precise estimates of the effect size of acute bouts of MVPA on EFs and 2) incorporating a more comprehensive and unbiased data synthesis. Collectively, our results provide compelling evidence for the transient beneficial effects of acute bouts of MVPA on EFs in children with ADHD.

Furthermore, the current meta-analysis went one step further by addressing the general versus selective effect of single bouts of MVPA between task components requiring low and high EF demand. Although the current study is one of the first to indicate a generally facilitative effect of acute MVPA on EF in children with ADHD, pharmacological research data from children with ADHD may support these findings. A previous meta-analysis indicated that psychostimulant medications, such as methylphenidate, elicit small but positive effects (effect sizes = 0.24–0.42) on performance across tasks with lower and higher EF demand in individuals with ADHD (Tamminga et al., 2016). Considering that acute bouts of MVPA may modulate EFs via the same neurobiological mechanisms as psychostimulant medicine (Berridge et al., 2006),

Table 2
Meta-analysis of the effects of single bouts of MVPA on EFs.

Task outcomes	Effect size and precision (random model)			Heterogeneity			Publication bias	
	N	Estimate (95% CI)	p-value	Q-value	p-value	I^2	Classic fail-safe N	Egger's regression test (t-value, p-value)
Low EFs	10	0.32 (0.123, 0.517)	0.001	17.797	0.038	49.43	42	1.77, 0.11
High EFs	10	0.25 (0.130, 0.371)	<0.001	7.912	0.543	0	38	1.55, 0.16

Notes. N = number of effect size; EFs = executive functions; MVPA = moderate-to-vigorous physical activity.

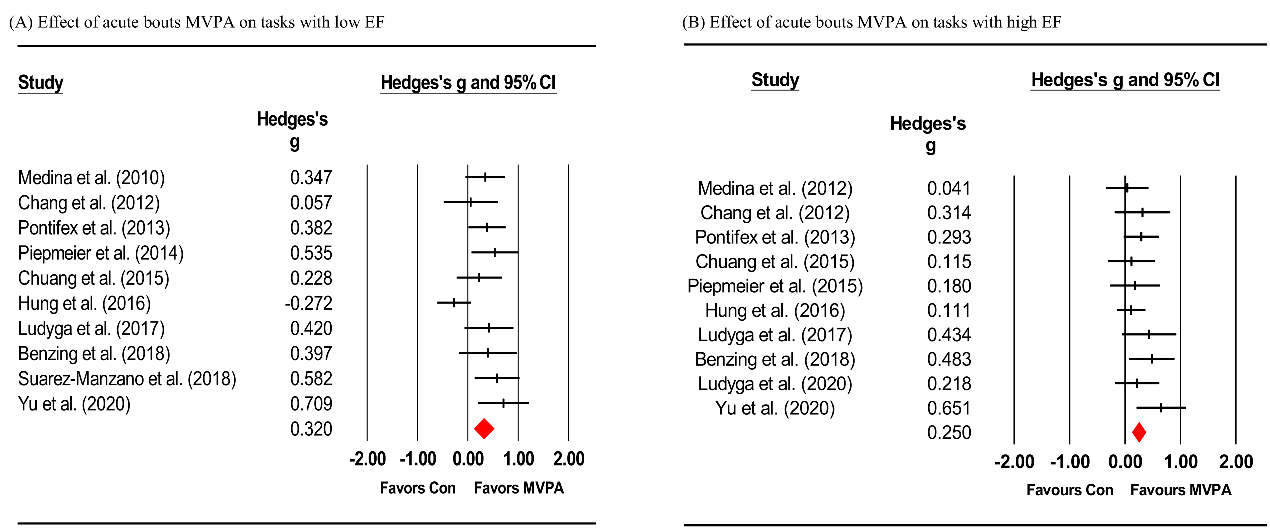

Fig. 3. Forest plot of the effect of MVPA on EFs.
Note. EFs = executive functions; Con = control group/condition; MVPA = moderate-to-vigorous physical activity; CI = confidence interval.

it is not surprising that acute bouts of MVPA have a generally facilitative effect on EFs with small positive effects ($g = 0.25–0.32$) in children with ADHD. Given that studies have indicated that pharmacotherapy can be accompanied with physical and psychological adverse effects in ADHD (Newcorn et al., 2010; Swanson et al., 2007), this study offers important clinical implications for acute bouts of 15–30 min MVPA as a non-pharmaceutical adjunctive treatment option with minimal adverse effects to temporarily facilitate EFs in children with ADHD.

Some limitations should be acknowledged. First, prior research has found that the effects of a single bout of PA on EFs may be moderated by age, such that PA benefits EFs only in preadolescents (6–12 years old), but not adolescents (13–17 years old) (Ludyga et al., 2016). However, we argue that age was unlikely to be a confounder in our findings because only three studies included in our meta-analysis recruited adolescents aged between 11 and 16 years and most participants (~68%) in these studies were 13 years or younger upon participation. Further, no prior research has examined the effects of acute MVPA on cognition in children and adolescents with ADHD across the developmental spectrum, as such the moderating role of age is still underexplored. Second, given that this study specifically focused on the effects of acute bouts of MVPA on low and high EFs to formulate specific exercise prescription for transiently improving EFs in children with ADHD, the implications may be limited by several potential moderators such as PA types and EF subdomains. Such generalizable effects could be accounted for, at least in part, by the shared neural circuits in the three core EF subcomponents, including frontoparietal and dorsal attention networks (Cole et al., 2013; Duncan, 2013), and that there seems to be a greater unidimensionality of EFs in school-aged children (Karr et al., 2018). In addition, empirical and meta-analytical data indicate that the acute effects of MVPA might be generalizable across different subcomponents of EF in a healthy population (Chen et al., 2014; Liu et al., 2020; Ludyga et al., 2016; Moreau & Chou, 2019). Nevertheless, future work is necessary to investigate these issues to extend the literature. Third, given that most of the included studies utilized crossover posttest designs, this design may possibly be affected by potential changes induced by the initial experimental condition. Although recent meta-analyses indicated that the effects of acute exercise on EF were not moderated by studies with or without baseline cognitive testing (Moreau & Chou, 2019), future studies are encouraged to use a randomized crossover pre-posttest study design (Pontifex et al., 2019).

5. Conclusions

Findings from the current meta-analytical review suggest that a single bout of MVPA has a general facilitative effect on tasks that modulate the EF demand in children with ADHD. The results from this meta-analysis suggest a small positive effect ($g = 0.25–0.32$) of a single bout of MVPA on the performance of tasks requiring lower and higher EFs in children with ADHD. The current study shows that a single bout of MVPA could serve as a nonpharmaceutical adjunctive treatment option with minimal adverse effects for childhood ADHD by transiently facilitating EFs.

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Declaration of interests

Given their role as Editorial Board members, Chang Y.-K. and Hung T.-M. had no involvement in the peer-review of this article and had no access to information regarding its peer-review. All other authors have declared no conflicts of interest relevant to the content of this article

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2021.102097.

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