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Acute effects of physical activity on cognitive function in children and adolescents with attention-deficit/hyperactivity disorder: A systematic review and meta-analysis

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ABSTRACT

Attention-deficit/hyperactivity disorder (ADHD), one of the most common neurodevelopmental disorders in children and adolescents, is typically managed with medications which are associated with negative side effects. Therefore, non-pharmacological treatments, such as physical activity, are an attractive option. The aim of this meta-analysis was to explore the effects of acute physical activity on cognition in children and adolescents with ADHD. A comprehensive search of three literature databases yielded 14 studies for inclusion. An overall meta-analysis was conducted alongside sub-group analyses for cognitive domain, physical activity characteristics, and timing of cognitive measurements. Results revealed a small beneficial effect of physical activity on cognitive function (SMD = 0.18, [0.12,0.25], $p < 0.01$). Sub-group analyses revealed beneficial effects of physical activity on the domains of cognitive flexibility (SMD = 0.21, [0.09,0.32], $p < 0.01$), attention (SMD = 0.20, [0.09,0.32], $p = 0.001$), and inhibitory control (SMD = 0.18, [0.03,0.33], p = 0.02), but not memory ($p = 0.87$). Cognitive benefits also differed depending on physical activity duration (<10 min, $p = 0.27$; 11–20 min, SMD = 0.23, [0.14,0.31], $p < 0.01$; >20 min, SMD = 0.13, [-0.00,0.26], $p = 0.05$), and modality (running, SMD = 0.21, [0.12,0.29], $p < 0.01$; 'other', SMD = 0.39, [0.18,0.61], $p < 0.01$; cycling, $p = 0.35$), and the timing of cognitive measurement following physical activity (immediately, SMD = 0.17, [-0.01,0.35], $p = 0.06$; 2–10 min, SMD = 0.21, [0.12,0.30], $p < 0.01$; >10 min, SMD = 0.19, [-0.09,0.47], $p = 0.19$). Overall, physical activity has a positive acute effect on subsequent cognition in children and adolescents with ADHD, though effects may be domain specific and influenced by the duration and modality of physical activity. These findings have practical implications for those interested in using physical activity to enhance cognition in children and adolescents with ADHD.

Attention-deficit/hyperactivity disorder (ADHD) has been suggested to be the third most common neurodevelopmental disorder in children and adolescents (Polanczyk, Salum, Sugaya, Caye, & Rohde, 2015). ADHD is estimated to have a prevalence of 3%–7% in children and adolescents globally (Diagnostic and Statistical Manual of Mental Disorders; APA, 2013; Sayal, Prasad, Daley, Ford, & Coghill, 2018) and is more prevalent in boys, with a commonly reported 3:1 ratio compared to girls (Arnett, Pennington, Willcutt, DeFries, & Olson, 2015; Wittchen et al., 2011). ADHD symptoms are often recognisable from early childhood (APA, 2013); however, ADHD is most commonly diagnosed at the age of 12 years in boys, and aged 16 years in girls (Danielson et al., 2018). ADHD has three sub-groups; predominantly inattentive, predominantly hyperactive/impulsive or a combined presentation (DSM-5, 2013). The diagnosis of ADHD involves the individual meeting six or more of the DSM-5 criteria, where all symptoms must have been present prior to 12 years of age; and the individual must have shown symptoms in at least two settings, for instance at school and at home (DSM-5, 2013). Recognisable symptoms and behaviours associated with the disorder include, but are not limited to, the inability to maintain attention, frequent fidgeting, lack of patience, and an inability to follow instructions or organise tasks and activities (APA, 2013; DSM-5, 2013).

These ADHD symptoms and behaviours are often associated with lower academic performance (Silva et al., 2020) and impaired cognitive functioning (Claesdotter, Cervin, Åkerlund, Råstam, & Lindvall, 2018)

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in children, which may in turn affect their future academic achievements (Arnold, Hodgkins, Kahle, Madhoo, & Kewley, 2020). This is unsurprising given that cognitive function is comprised of a multitude of domains which are all key to academic success (Jacob & Parkinson, 2015; Pascual, Muñoz, & Robres, 2019). These domains include memory, attention, perception, executive function (working memory, inhibitory control, and cognitive flexibility), psychomotor, and language (Harvey, 2019; Schmitt, Benton, & Kallus, 2005). Executive function, which is comprised of high-order cognitive processes and skills contributing to inhibitory control, cognitive flexibility, and working memory (Ahmed & Miller, 2011; Best & Miller, 2010; Carlson, Moses, & Claxton, 2004), has been shown to be the domain of cognitive function most commonly affected by ADHD, although ADHD is a condition with a great deal of heterogeneity (Kofler et al., 2019; Martel, Nikolas, & Nigg, 2007; Schoemaker et al., 2012). This is of particular interest given that executive function is also suggested to be the most important cognitive domain for academic achievement (Best, Miller, & Naglieri, 2011).

In children and adolescents, ADHD is typically initially treated with non-pharmacological treatments such as diet or lifestyle management (Chaplin, 2018), parent training programmes, and psychoeducation (NHS, 2018). There is, however, a lack of evidence of the efficacy for such non-pharmacological interventions (Sonuga-Berg et al., 2016). Where these initial treatments are not successful in managing ADHD, medications such as methylphenidate, lisdexamfetamine, and dexamphetamine are commonly prescribed (NHS, 2018). Adherence to such medication is often dependent on ADHD severity and willingness to take the medication, alongside parental perceptions of medication use (Charach & Fernandez, 2013). Although medication helps to control ADHD symptoms and has demonstrated improvements in cognitive function in children and adolescents with ADHD (Yildiz, Sismanlar, Memik, Karakaya, & Agaoglu, 2011), ADHD medication has several negative side effects which may contribute to poor adherence; including sleep problems, mood disturbances, weight loss and headaches (Catalá-López et al., 2017; Toomey, Sox, Rusinak, & Finkelstein, 2012; Yildiz et al., 2011). With regards to non-pharmacological lifestyle management, physical activity has been suggested to be a potential intervention for the management of ADHD symptoms and behaviours (Gapin & Etnier, 2014; Vysniauske, Verburgh, Oosterlaan, & Molendijk, 2020; Welsch et al., 2021); yet physical activity is not commonly used by healthcare providers as an additional or alternative ADHD management technique.

Recently, systematic reviews have concluded that there are positive effects of both acute (single-bouts of physical activity) and chronic (physical activity conducted multiple times a week, over an extended period of time) physical activity interventions on cognitive function in children and adolescents with ADHD (Cornelius, Fedewa, & Ahn, 2017; Grassmann, Alves, Santos-Galduróz, & Galduróz, 2017; Liang, Wong, Sum & Sit, 2021; Neudecker, Mewes, Reimers, & Woll, 2019; Suarez-Manzano, Ruiz-Ariza, Torre-Cruz, & Martínez-López, 2018). In regard to the chronic effects of physical activity, one study concluded that 5–20 weeks of 30–90 min (per week) of moderate to vigorous exercise demonstrates a chronic positive effect on overall cognition and behaviour in children and adolescents (Suarez-Manzano et al., 2018). The most recent systematic review and meta-analysis by Welsch et al. (2021) primarily focused on the effect of chronic exercise interventions on executive functioning domains in children and adolescents with ADHD. It was found that chronic exercise interventions showed beneficial effects for the domains of inhibitory control, cognitive flexibility and working memory in children and adolescents with ADHD compared to no treatment controls. Therefore, overall, the findings of Welsch et al. (2021) tentatively provide evidence that chronic exercise interventions are beneficial across cognitive domains in children and adolescents with ADHD.

A number of recent reviews have shown that acute bouts of physical activity have a small but positive effect on subsequent cognitive function in neurotypical children and adolescents (Chang, Labban, Gapin, & Etnier, 2012; Donnelly et al., 2016; Williams, Hatch, & Cooper, 2019). These effects have been demonstrated across a range of domains of cognition, including attention (Altenburg, Chinapaw, & Singh, 2016; Park & Etnier, 2019), working memory (Koutsandréou, Wegner, Niemann & Budde, 2015) and executive function (Verburgh, Königs, Scherder, & Oosterlaan, 2014). Therefore, it is logical that acute bouts of physical activity could be a potential intervention to improve cognitive function in children and adolescents with ADHD.

There are suggestions from the literature in neurotypical young people, and from narrative reviews in children and adolescents with ADHD, that the key moderating variables in the physical activity-cognitive relationship are characteristics of the physical activity task (e.g., duration and modality) and the timing of cognitive tests post-physical activity (Erickson et al., 2019; Pesce, 2009; Williams et al., 2019). Specifically, the proposed physical activity-cognition framework by Williams et al. (2019) suggested that both physical activity characteristics (duration, intensity and modality) and issues regarding the measurement of the cognitive variables (domains measured, and timing of the tests) will influence the acute effects of physical activity on subsequent cognition in young people. Additionally, participant characteristics, such as age, physical fitness, and cognitive ability, were also suggested to influence this relationship (Williams et al., 2019). Furthermore, Pesce (2009) discussed the effects of individual and task constraints on the physical activity-cognition relationship, highlighting how individual constraints such as physical fitness, motor coordination skills, cognitive expertise, age, and gender; alongside task constraints including exercise intensity, duration and complexity, cognitive task complexity and time relation between physical activity and cognitive task, influence this relationship.

Specifically, Chang et al. (2015) investigated the impact of exercise duration on subsequent cognition in neurotypical young adults (20–22 y). The findings suggest that 20 min of moderate-vigorous physical activity results in faster Stroop performance reaction time; compared to a resting, 10 min or 40 min physical activity condition. Furthermore, in neurotypical adolescents, Hatch et al. (2021) investigated the effects of 30 min exercise, 60 min exercise and a resting control condition on thirty-eight adolescents, highlighting the greatest cognitive benefits following 30 min of high-intensity intermittent running, compared to 60 min and the resting control. Although Chang et al. (2015) and Hatch et al. (2021) provided evidence of the importance of duration, perhaps it is a combination of task constraints that contributes to the beneficial effects of physical activity on cognition. This suggestion is supported by evidence of improved executive function after 30 min of open-skill physical activity (badminton), compared to closed-skill physical activity (running) (Hung, Tseng, Chao, Hung, & Wang, 2018); identifying modality of physical activity to be a key moderator of the physical activity-cognition relationship. Finally, the timing of the completion of cognitive tests following physical activity has also been shown to play an important role in determining post-activity cognitive effects, whereby the greatest beneficial effects were found when the tests were completed 11–20 min following physical activity (Chang, Liu, Yu, & Lee, 2012). Therefore, it is clear that key moderating variables such as characteristics of the physical activity (e.g., duration, modality), and the timing of cognitive tests following physical activity should be considered and assessed in future research examining the effects of physical activity on cognition. Moreover, these effects are yet to be fully examined in ADHD populations, with no synthesis or meta-analysis having pooled the available data from individual studies to address these important questions.

Whilst a review by Cornelius et al. (2017) began to highlight the importance of these potential moderators in children and adolescents with ADHD, due to the lack of research when the previous review was conducted, only type of physical activity was found to affect cognitive function performance, whereby aerobic physical activity such as running and cycling elicited greater improvements on subsequent cognition compared to non-aerobic activities. Furthermore, these moderators have not yet been examined meta-analytically in young people with ADHD. It is therefore important to reassess the effects of these moderating factors on cognition in children and adolescents with ADHD.

Whilst much of the literature has focused on the chronic effects of physical activity interventions on cognitive function in children and adolescents with ADHD, less emphasis has been placed on the acute effects of a single-bout of physical activity on subsequent cognition in this population; and, in particular, how the aforementioned moderating variables (such as the intensity, duration and modality of the activity) influence these effects. The effects of acute physical activity interventions do however have significant importance for healthcare practitioners and educationalists working within this population; and the potential practical utility of a single-bout of physical activity to enhance cognition and behaviour in children and adolescents with ADHD is yet to be fully addressed.

Overall, it appears that the existing systematic reviews investigating the effects of acute physical activity interventions on cognitive function do not use a meta-analytical approach. Therefore, there is currently limited knowledge regarding the size of the effect of acute physical activity on cognition in children and adolescents with ADHD. Furthermore, with recent increased attention within the research literature towards the effects of acute physical activity interventions on children and adolescents with ADHD, it is important to provide an up-to-date review of the literature, whilst adopting a meta-analytical approach to provide insight regarding the size of the effect. Furthermore, the effect of key moderating variables (such as the intensity, duration, and modality of physical activity) should be meta-analytically examined, in order to provide practical recommendations for practitioners. Enhancing the understanding regarding the effects of acute physical activity interventions could also inform the chronic, longer-term effects; given that acute bouts of physical activity are likely to contribute to, and accumulate to, any chronic adaptations. Therefore, understanding the acute effects may provide mechanistic insight regarding the chronic effects.

In conclusion, whilst it appears that chronic physical activity interventions are beneficial for cognition in children and adolescents with ADHD, the evidence regarding the acute effects of a single-bout of physical activity are poorly understood. Therefore, the primary aim of the present systematic review and meta-analysis is to investigate the effects of acute physical activity interventions, compared to a resting condition, on cognitive function in children and adolescents aged 5–18 years with ADHD. A secondary aim is to examine the effects across moderating factors; domains of cognition, mode of physical activity, type of study design, duration of physical activity, and timing of administration of cognitive function tests post physical activity.

1. Method

This meta-analysis followed the recommendations provided by the preferred reporting items for systematic reviews and meta-analyses (PRISMA-P) checklist (Moher et al., 2015).

1.1. Search process

A comprehensive electronic literature search of three databases of literature (PubMed, ProQuest & Web of Science) was simultaneously conducted (see Fig. 1). The primary search terms were as follows: (1) “attention deficit hyperactivity disorder” (“ADHD” or “attention deficit disorder” or “ADD” or “impulsivity” or “hyperactivity”), (2) “young

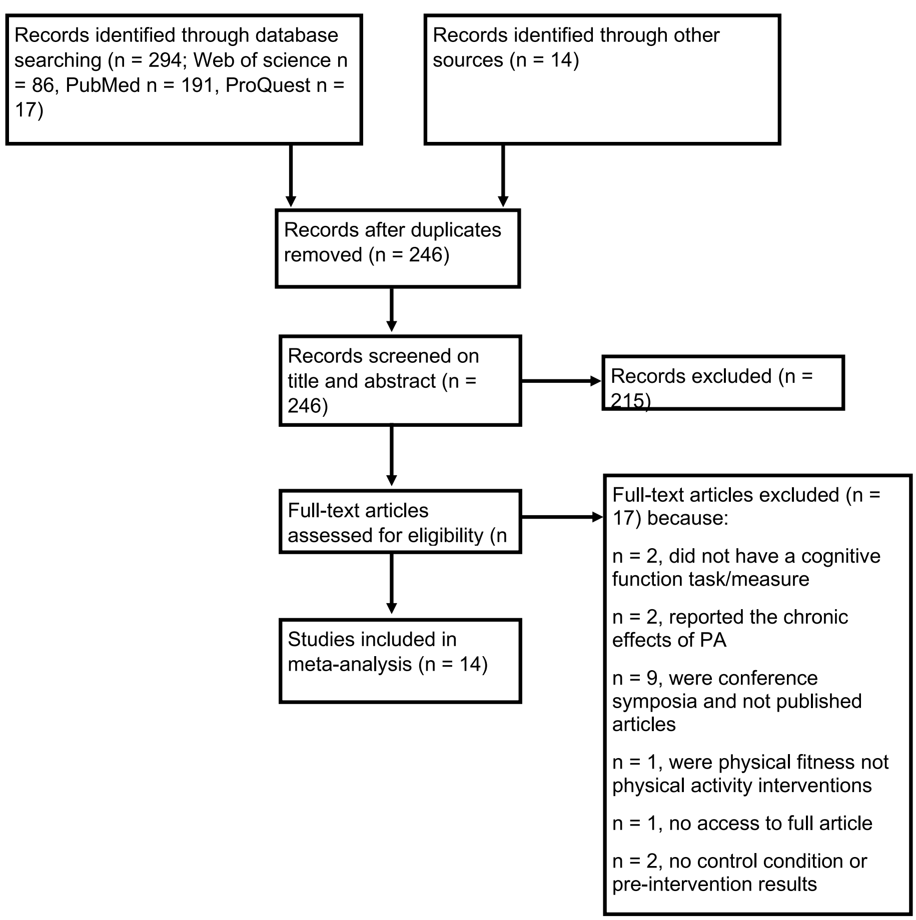

Fig. 1. PRISMA flow chart outlining search strategy for systematic review and meta-analysis.

people" ("children" or "adolescents" or "juvenile" or "minors" or "pubescent"), (3) "physical activity" ("exercise" or "acute exercise" or "sport" or "single bout exercise" or "aerobic") and (4) "cognitive function" ("cognition" or "executive function" or "inhibitory control" or "working memory" or "attention" or "cognitive flexibility"). The search was restricted to studies conducted with human participants, written in English and those published until July 2021. A manual search was additionally conducted, and reference lists of selected articles were screened for relevant articles which were not found during the initial search. Once the search was complete, duplicates were removed, and titles and abstracts were screened for relevance. Full texts were then screened following the inclusion criteria (see Fig. 1 for more detailed record of search process).

The literature search resulted in 246 article titles and abstracts being reviewed, 31 full-text articles being screened, of which 14 articles were included in the systematic review and meta-analysis. Reasons for exclusion of the 17 studies removed after full-text screening are described in Fig. 1. The screening process was conducted by two investigators and any discrepancies were resolved by consulting a third investigator.

1.2. Inclusion criteria

The decision to include articles in the final sample was based on the following criteria: (a) the study must have investigated the effects of an acute physical activity (single-bout) intervention on cognition in children and adolescents with ADHD; (b) participants must be children or adolescents aged 5–18 years; (c) participants must have a diagnosis of ADHD by a psychiatric physician or meet the criteria outlined in validated rating scales (e.g., DSM-5); (d) the studies must report cognitive function test results either 'pre' intervention or have a comparison group (e.g. resting control group); and (e) the studies must have measured at least one cognitive function outcome (see Table 1 for included studies).

1.3. Data extraction and management

The data were extracted independently by the lead author. Key demographic participant information (e.g., number, sex, age, comorbidity, and medication use), study characteristics (e.g., number of experimental sessions, familiarisation trials, study design, physical activity intervention intensity and duration and control condition duration) and cognitive function characteristics (e.g., cognitive function tests, cognitive function domains and the means ± SD for both intervention and control conditions) were collated. Once all data were extracted, four authors discussed the results of the included studies where there was a lack of clarity or understanding of the reported results.

Corresponding authors of studies with missing data from the published articles (Miklós, Komáromy, Futó, & Balázs, 2020; Piepmeier et al., 2015) were contacted to request missing means and standard deviations for the cognitive function tests to facilitate inclusion in the meta-analysis.

1.4. Data synthesis

Where studies contained multiple physical activity conditions (e.g., medicated group and a non-medicated group, or multiple durations of physical activity) compared to a control condition, the physical activity conditions were combined to create a single pairwise comparison group, as recommended in the Cochrane Handbook (Higgins et al., 2019). Most of the studies included in the meta-analysis used multiple cognitive function tests with a number of outcome measures (e.g., reaction time and error rate). Therefore, each measure was inputted separately (due to the variety of units reported for each measure) and a standardised mean difference (SMD) effect size was calculated (see Supplementary Table 3 for details on outcome measures assessed). Where a control condition was absent in one study (Craft, 1983), the pre-intervention results were used as a control; providing a pre-post comparison and allowing inclusion in the meta-analysis.

1.5. Meta-analysis

The meta-analysis was conducted using Review Manager software (RevMan, 5.4.1, The Cochrane Collaboration, 2020). The initial meta-analysis included measures across all cognitive function domains (Fig. 2). Subsequently, a separate sub-analysis was conducted for each cognitive domain measured by the included studies, namely cognitive flexibility, attention, memory, and inhibitory control (Fig. 3). A further sub-analysis was conducted to examine the effect of physical activity duration, categorised as ≤ 10 min, 11–20 min and >20 min. A third sub-analysis was also conducted to investigate the study design, which was coded as within-subject design or between-subject design; one study was not included in this sub-analysis due to the use of a mixed study design (Mahon et al., 2013). A fourth sub-analysis was conducted for the mode of physical activity, categorised as 'running', 'cycling', and 'other'. The group named 'other' grouped any alternative physical activity that was not running or cycling and included trampolining, exergaming, and

Table 1
Risk of bias for included studies.

Article	Domain 1: randomization process	Domain S: period and carry over effects	Domain 2: effect of assignment	Domain 3: missing data	Domain 4: measurement of outcome	Domain 5: selection of reported result	Overall risk score
Craft (1983)	?	✓	✓	✓	✓	✓	✓
Medina et al. (2010)	×	?	✓	✓	✓	✓	?
Chang, Labban, Gapin, and Etnier (2012)	✓	NA	✓	✓	✓	✓	✓
Mahon et al. (2013)	?	✓	?	✓	✓	✓	✓
Pontifex et al. (2013)	?	✓	✓	✓	✓	✓	✓
Chuang et al. (2015)	?	✓	✓	✓	✓	✓	✓
Piepmeier et al. (2015)	✓	✓	✓	✓	✓	✓	✓
Gawrilow et al. (2016)	✓	NA	✓	✓	✓	✓	✓
Hung et al. (2016)	?	✓	✓	✓	✓	✓	✓
Ludyga et al. (2017)	?	✓	✓	✓	✓	✓	✓
Benzing et al. (2018)	✓	NA	✓	✓	✓	✓	✓
Ludyga et al. (2020)	✓	NA	✓	✓	✓	✓	✓
Miklós et al. (2020)	?	NA	✓	✓	✓	✓	✓
Bigelow et al. (2021)	?	✓	✓	✓	✓	✓	✓

Note. Domain S was completed for cross-over studies, low risk is indicated by a ✓, some concerns is indicated by a ?, and high risk is indicated by a ×.

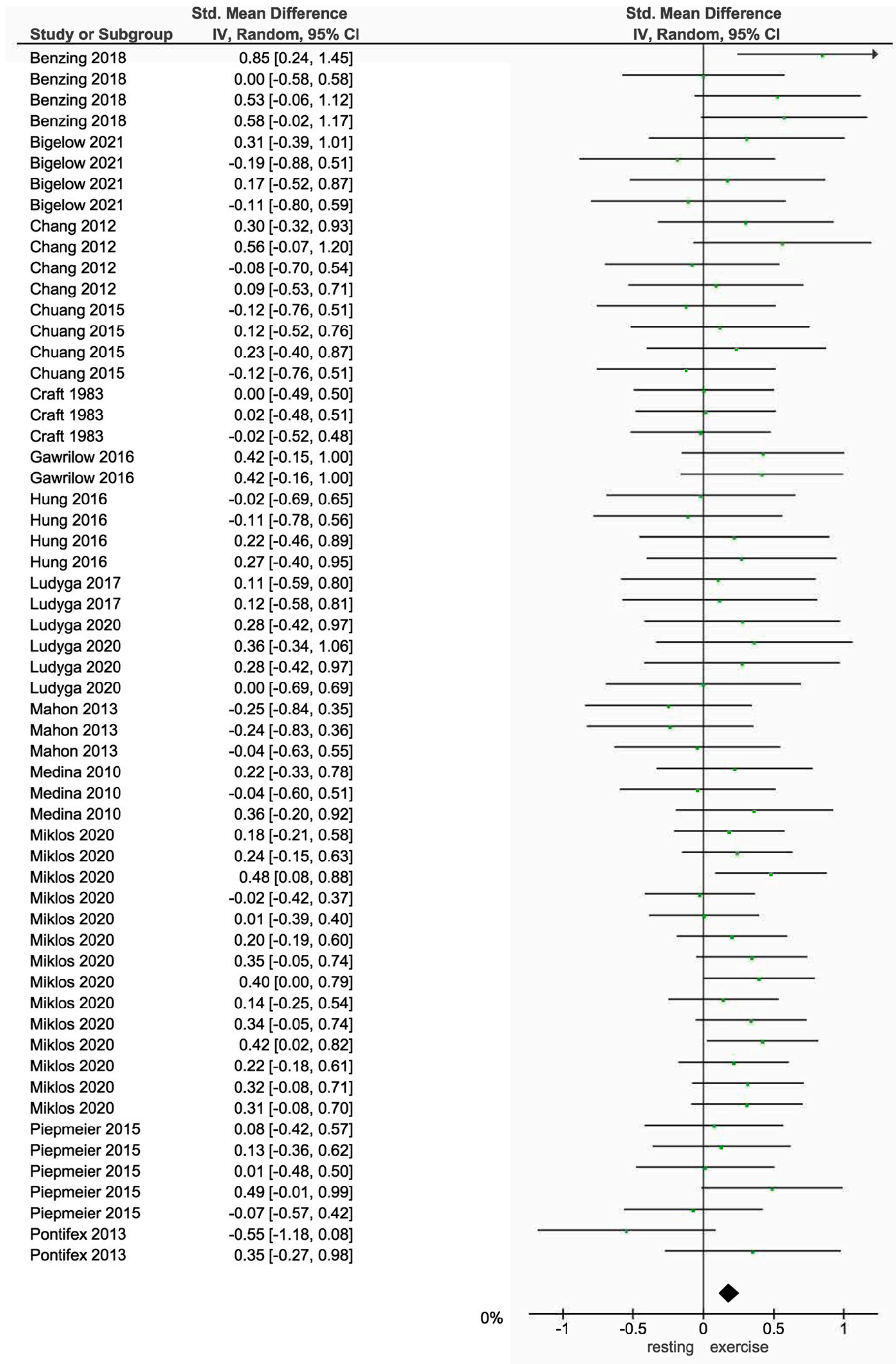

Fig. 2. *Forest plot showing overall effect size of included studies (SMD = 0.18; 95% Cl [0.12,0.25]; p < 0.01; I² = 68%).*

coordinative tasks. One study was included in two groups due to the use of two different physical activity interventions (Ludyga et al., 2017). Finally, a sub-group analysis was conducted looking at the timing of completion of the cognitive function tests post-intervention. Nine out of the 14 studies included in the meta-analysis reported timing post-intervention and were therefore included in the sub-group analysis. One study (Pontifex, Saliba, Raine, Picchietti, & Hillman, 2013) stated that the timing of their post-physical activity cognitive measurements were based on a target heart rate rather than specific timing; this study was therefore not included in this sub-group analysis. The groups were categorised as 'immediately post-intervention', '2–10 min post--intervention' and '> 10 min post intervention'.

The results from the meta-analyses are reported as standardised mean difference (SMD) using a random effect model, due to a number of studies assessing the same outcome (e.g., cognitive domain) but using different tests (e.g., Stroop test and Flanker) and outcome measures (e.g., response time and accuracy); in line with recommendations (Cochrane Handbook, Version 6.2, 2021). Effect sizes were interpreted as per convention ($\leq$0.2 small effect, $\leq$ 0.5 medium effect, $\leq$ 0.8 large effect) (Cochrane Handbook, Version 6.2, 2021). Statistical significance was accepted as $p < 0.05$. Heterogeneity was recognised as small (0–40%), moderate (40–60%), substantial (50–90%) and considerable (75–100%), in line with recommendations (Cochrane handbook, Version 6.2, 2021).

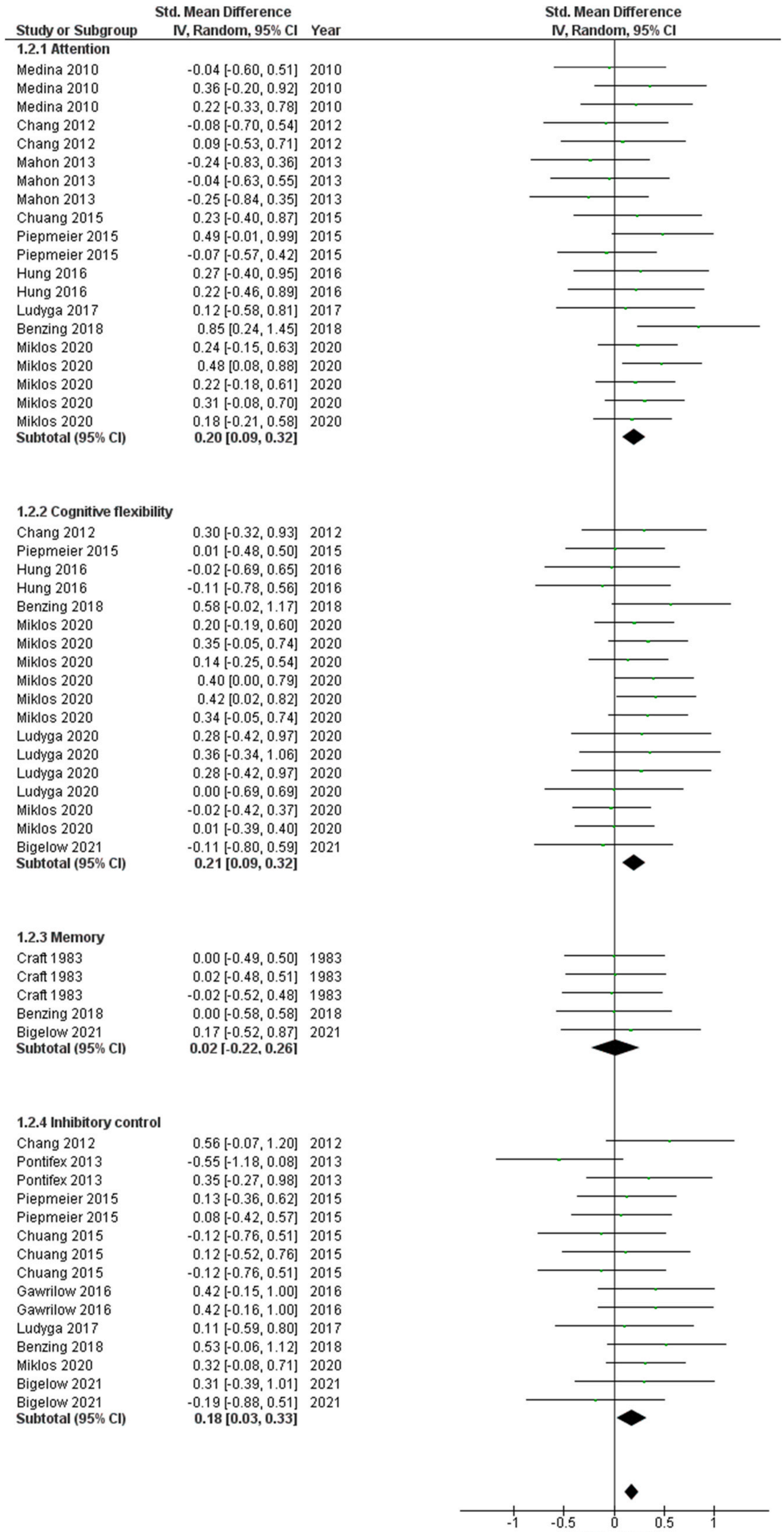

Fig. 3. *Forest plot showing sub-group analysis. Note.* Attention (*SMD = 0.20, p = 0.001;* $I^2 = 56\%$), cognitive flexibility (*SMD = 0.19, p = 0.001;* $I^2 = 42\%$), memory (*SMD = 0.02, p = 0.87;* $I^2 = 0\%$) and inhibitory control (*SMD = 0.21, p = 0.002;* $I^2 = 46\%$).

1.6. Risk of bias

The studies were assessed for their quality using the Cochrane Collaboration's tool to assess Risk of Bias (Higgins et al., 2019). The revised tool for risk of bias (RoB 2) was used to assess risk of bias in the included studies. Each study was carefully assessed, and a risk-of-bias judgement was made by following the suggested algorithm for each domain assessed. As per recommendations, the domain 'S' (signalling) which assessed the risk of bias arising from period and carryover effects, was only completed for the crossover studies (Sterne et al., 2019).

2. Results

2.1. Description of included studies

A total of 14 studies and 58 effect sizes were included in the meta-analysis. The number of participants with ADHD in the studies ranged from 14 to 100 (11% of the total sample population were female), with a total participant sample size of 446 across all of the included studies. The participant's ages ranged from six years to 16 years. Twelve out of the fourteen studies reported the number of participants on medication, with 66% of all participants in the included studies regularly taking medication (two studies did not state the number of participants using medication (Bigelow, Gottlieb, Ogrodnik, Graham, & Fenesi, 2021; Pontifex et al., 2013). Medication was not chosen for a sub-group analysis due to the variability of medications and protocol for medication use for participation in studies (e.g., stop using medication 24 h before intervention).

Of the included studies, 12 directly measured the intensity of physical activity to confirm a moderate to vigorous intensity, whilst two studies (Gawrilow, Stadler, Langguth, Numann, & Boeck, 2016; Medina et al., 2010) stated that they used moderate to vigorous physical activity but did not directly measure this (physical activity intensity for each study is outlined in Table 2). Physical activity duration varied from 1 min to 30 min (mean ± SD: 19 ± 10 min). Of the physical activity interventions, six of the studies used physical activity on a cycle ergometer (Bigelow et al., 2021; Craft, 1983; Ludyga et al., 2017, 2020; Mahon et al., 2013; Piepmeier et al., 2015), with one study also using a coordinative task (Ludyga et al., 2017), and five studies used a treadmill to complete either continuous or interval running (Chang, Liu, et al., 2012; Chuang, Tsai, Chang, Huang, & Hung, 2015; Hung, Huang, Tsai, Chang, & Hung, 2016; Medina et al., 2010; Pontifex et al., 2013). Miklós et al. (2020) used running as their physical activity condition but did not state whether they used a treadmill. One study used trampolining as their physical activity condition (Gawrilow, Stadler, Langguth, Naumann, & Boeck, 2016), and the final study used exergaming (Benzing, Chang, & Schmidt, 2018) (see Table 2 for an overview of the included studies).

2.2. Risk of bias

The results from the risk of bias revealed that five studies were low risk across all of the domains (Table 1). All of the included studies showed low risk across the domains of missing data, measurement of the outcomes and selection of the reported results. The randomization process category resulted in one study having a high risk (Medina et al., 2010) and eight having some concerns (Table 1). Overall, the risk of bias assessment revealed that there were some concerns in at least one category for eight of the included studies; however, these were deemed to be low risk in the overall judgement. Although one study was high risk in one domain, the overall risk of bias judgement was decided to be 'some concerns' and would not substantially lower the confidence of the result.

2.3. Meta-analyses

2.3.1. Overall effect

The overall effect suggested a statistically significant small effect favouring acute bouts of physical activity compared with a control condition, to improve cognitive function in children and adolescents with ADHD (SMD = 0.18; 95% Cl [0.12, 0.25]; $p < 0.01$). The test for heterogeneity indicated substantial heterogeneity across the effect sizes in the overall sample (Q (41.65), $df = 13$, $I^2 = 68\%$) (Fig. 2).

2.3.2. Sensitivity analysis

A sensitivity analysis was conducted by removing each effect size from the overall meta-analysis one at a time, and then returning them to the overall sample. The sensitivity analysis revealed a stable effect size, that ranged from SMD = 0.19 [0.12, 0.26], $p < 0.001$ to SMD = 0.18 [0.11, 0.24], $p < 0.001$ when each of the individual effect sizes were removed.

2.3.3. Cognitive domains

The sub-group analysis of the cognitive domains (Fig. 3) revealed that there was a statistically significant positive effect of acute physical activity on cognitive flexibility after an acute bout of physical activity compared to a control condition (SMD = 0.21, [0.09, 0.32], $p < 0.001$); and the test for heterogeneity showed moderate heterogeneity across the sample (Q (10.25), $df = 6$, $I^2 = 41\%$). Attention was revealed to have a statistically significant small effect following an acute bout of physical activity (SMD = 0.20, [0.09, 0.32], $p < 0.001$) with moderate to substantial heterogeneity (Q (16.04), $df = 8$, $I^2 = 50\%$). It was also shown that acute bouts of physical activity enhanced inhibitory control, with a statistically significant small effect (SMD = 0.18, [0.03, 0.33], $p = 0.02$); the test for heterogeneity showed moderate heterogeneity (Q (13.14), $df = 8$, $I^2 = 39\%$). However, the sub-analysis revealed that memory was not enhanced in children and adolescents with ADHD following an acute bout of physical activity (SMD = 0.02, [−0.22, 0.26], $p = 0.87$); with no heterogeneity (Q (0.22), $df = 2$, $I^2 = 0\%$). The test for subgroup differences was non-significant for cognitive domains (Q (2.00), $df = 3$, $p = 0.57$, $I^2 = 0\%$).

2.3.4. Physical activity intervention duration

Studies with physical activity interventions >20 min revealed a statistically significant small effect on cognitive function (SMD = 0.13, [−0.00, 0.26], $p = 0.05$); with moderate to substantial heterogeneity (Q (8.77), $df = 4$, $I^2 = 54\%$). The sub-analysis also revealed that physical activity interventions 11 min–20 min in duration showed a statistically significant small effect on cognitive function (SMD = 0.23, [0.14, 0.31], $p < 0.01$) with considerable heterogeneity (Q (26.55), $df = 5$, $I^2 = 81\%$). Finally, studies which used physical activity interventions ≤10 min in duration revealed no effect on cognition (SMD = 0.11, [−0.08, 0.30], $p = 0.27$) with moderate heterogeneity (Q (4.20), $df = 2$, $I^2 = 52\%$) (Fig. 4). The test for subgroup differences was non-significant for physical activity duration (Q (2.12), $df = 2$, $p = 0.35$, $I^2 = 6\%$).

2.3.5. Study design

The sub-analysis for study design (Fig. 5) revealed a statistically significant small effect for between-subjects design after acute physical activity interventions on subsequent cognition (SMD = 0.28 [0.19, 0.37], $p < 0.01$) and there was shown to be considerable heterogeneity (Q (17.42), $df = 4$, $I^2 = 77\%$). The effect for studies with a within-subjects design was not statistically significant (SMD = 0.09 [−0.02, 0.2], $p = 0.11$); the test for heterogeneity showed moderate heterogeneity (Q (12.35), $df = 6$, $I^2 = 51\%$). The test for subgroup differences showed a statistically significant difference for intervention study design

Table 2
Overview of included studies.

Study (year)	*n participants with ADHD (females)*	*Study design*	*PA duration (min)*	*PA intervention (exercise intensity)*	*Control condition*	*Cognitive function test (time between intervention and cognitive test completion)*	*Cognitive function domains measured*	Number of effect sizes *Total: 50*
Craft (1983)	31	Within	1, 5, & 10	Cycling at 18–20 km h^{-1} (170 beats·min^{-1})	Resting/0 min (pre-exercise)	Weschler Intelligence Scale for Children-revised digit span Weschler Intelligence Scale for Children – Revised - coding B Illinois test of psycholinguistic abilities (not stated)	Memory Visual sequential memory	3
Medina et al. (2010)	25	Within	30	10 loaded efforts for 2 min with 1 min rest on treadmill (intensity not stated – target HR 165–169 beats·min^{-1})	Stretching	Conners' continuous performance test II (not stated)	Attention	3
Chang, Labban, et al. (2012)	40 (3)	Between	30	Treadmill running (50–70% HRR)	Watched a running/exercise-related video	Stroop Test Wisconsin Card Sorting Test (immediately)	Inhibitory control Cognitive flexibility	4
Mahon et al. (2013)	22 (2)	Mixed	20	30 s cycling, followed by 30 s stationary rest (90% PWC)	Resting (pre-exercise)	Conners' continuous performance test II (immediately)	Attention	3
Pontifex et al. (2013)	20 (6)	Within	20	Aerobic exercise on a treadmill (65–75% HR_{max})	Seated reading	Eriksen Flanker Test (once HR returned to within 10% of pre-experimental condition levels)	Inhibitory control	2
Chuang et al. (2015)	19 (3)	Within	30	Treadmill running (60% HRR)	Watched video	Go/No Go test (~5 min)	Inhibitory control	4
Piepmeier et al. (2015)	14 (5)	Within	30	Continuous cycling (40–60 RPM/RPE between 5 and 7)	Watched Planet Earth documentary whilst sat on cycle-ergometer	Stroop test Tower of London Trail Making Test (~4 min)	Inhibitory control General executive function Cognitive flexibility	5
Gawrilow et al. (2016)	47	Between	5	Continuous bouncing on trampoline (stated vigorous intensity)	Coloured in pictures that depicted activities	Go/No Go task (not stated)	Inhibitory control	2
Hung et al. (2016)	34 (1)	Within	30	Running on treadmill (50–70% HRR)	Watched video	Task Switching Paradigm (not stated)	Cognitive flexibility	4
Ludyga et al. (2017)	16 (5)	Within	20	1. Cycling at moderate intensity (65–70% HR_{max}) 2. Coordinative exercises-object control skills and bilateral coordination skills	Watched documentary about exercise behavior in adults	Eriksen Flanker test (10 min)	Inhibitory control	2
Benzing et al. (2018)	46 (8)	Between	15	Exergame called "Shape up" (55–90% HR_{max})	Watching documentary about mountain running	Eriksen Flanker test Colour span backwards test (immediately)	Inhibitory control Visual working memory	4
Ludyga et al. (2020)	16 (5)	Within	20	Continuous cycling (65–75% HR_{max})	Watched documentary on exercise behavior in adults	Alternate Uses task (15–20 min)	Cognitive flexibility	4
Miklós et al. (2020)	100 (8)	Between	20	Interval running divided into 4 × 4 periods with 1 min slow walking breaks (60–80% HR_{max})	Watched cartoon video whilst seated	KiTAP Go/No Go test (4 min)	Attention Cognitive flexibility Inhibitory control	14
Bigelow et al. (2021)	16 (5)	Within	10	Cycling on a cycle ergometer (65–85% HR_{max})	Reading magazines	Stroop test Leiter-3 Reverse Memory subscale (immediately)	Inhibitory control Working memory Cognitive flexibility	4

Note. PA – physical activity; km·h^{-1} - Kilometres per hour; HRR - Heart Rate Reserve; HR_{max} - Maximum Heart Rate; PWC - Peak Working Capacity; RPE - Rating of Perceived Exertion, RPM - Revolutions Per Minute.

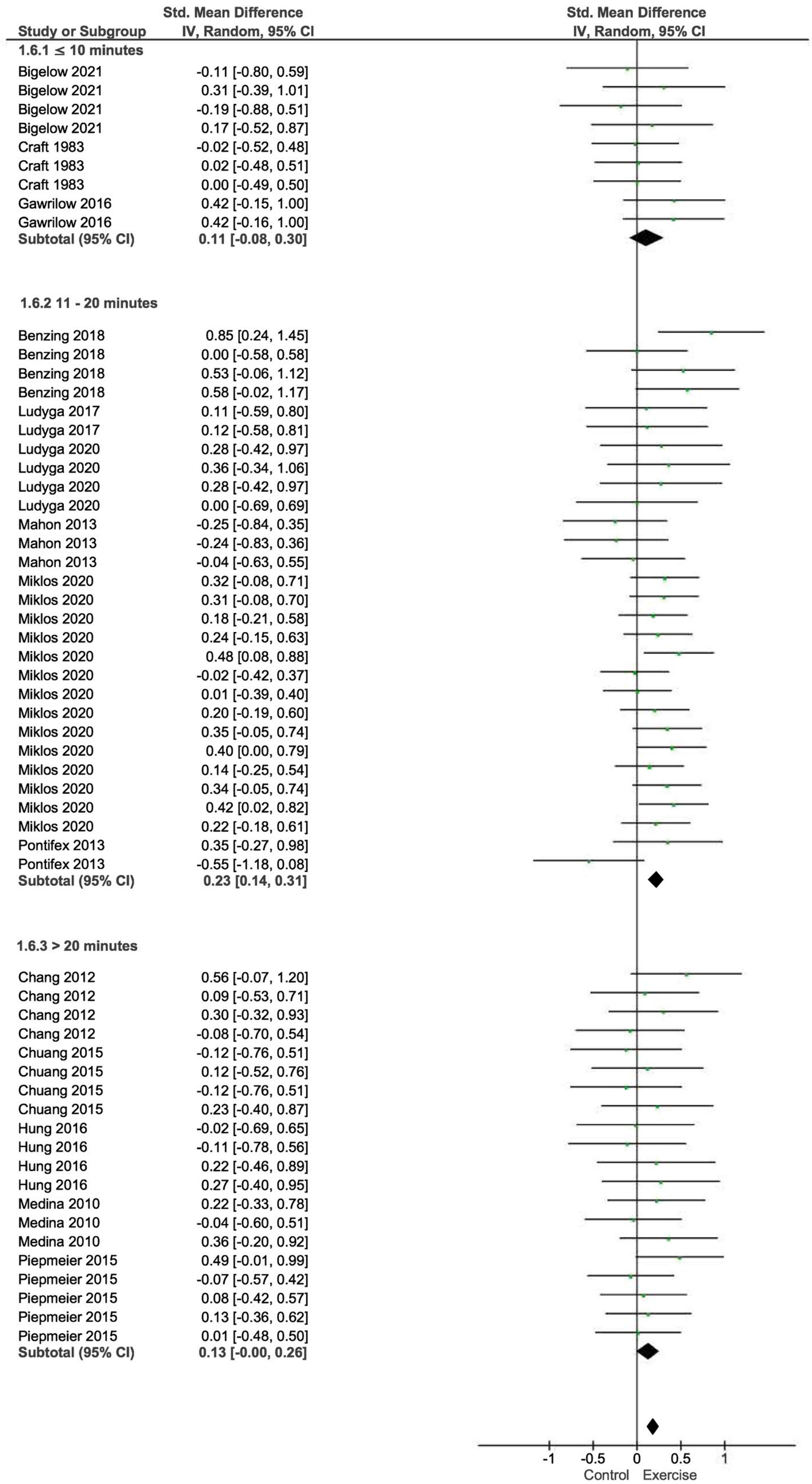

Fig. 4. *Forest plot showing sub-group analysis for physical activity duration. Note.* ≤ 10 min (*SMD = 0.11, p = 0.27;* I^2 *= 52%*), 11–20 min (*SMD = 0.23, p* < *0.01;* I^2 = *81%*) and >20 min (*SMD = 0.13, p = 0.05;* I^2 *= 54%*).

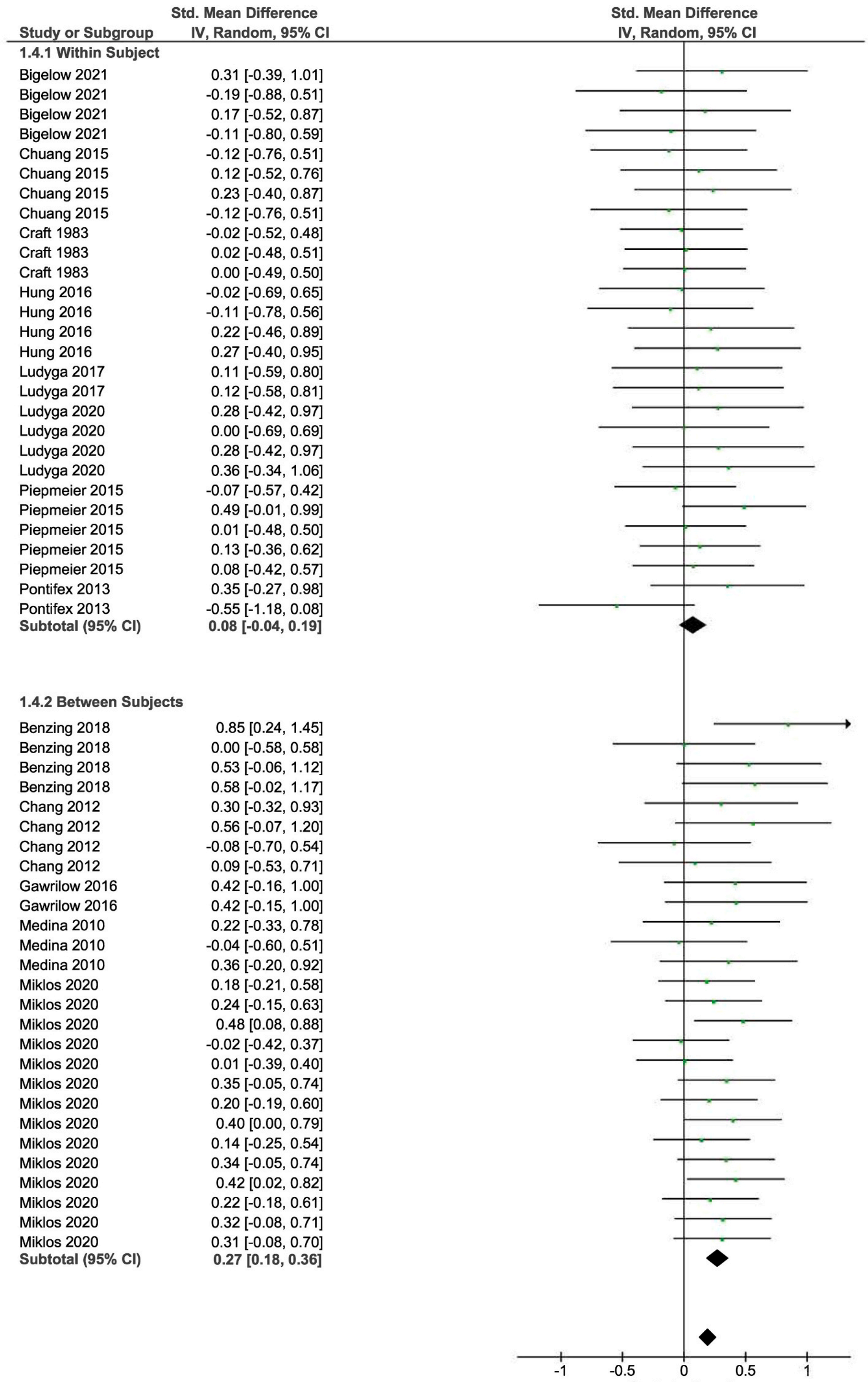

Fig. 5. *Forest plot showing sub-group analysis for study design. Note.* Within subject designs (*SMD* = *0.09, p* = *0.11;* I^2 = *51%*) and between subject designs (*SMD* = *0.28, p* < *0.01;* I^2 = *77%*).

(Q (7.17), $df = 1$, $p < 0.01$, $I^2 = 86\%$).

2.3.6. Modality of exercise

Modality of physical activity was categorised into 'running' interventions, 'cycling' interventions and 'other'. Studies that used modes of physical activity interventions which were not running, or cycling showed a statistically significant small effect on subsequent cognitive performance (SMD = 0.39 [0.18, 0.61], $p < 0.01$), and showed substantial heterogeneity (Q (5.78), $df = 2$, $I^2 = 65\%$). Running physical activity interventions also produced a statistically significant small effect on sequential cognitive function performance (SMD = 0.21 [0.12, 0.29], $p < 0.01$) and showed considerable heterogeneity (Q (20.27), $df = 5$, $I^2 = 75\%$). The sub-analysis showed that cognitive performance was not enhanced following cycling interventions (SMD = 0.06 [−0.07, 0.19], $p = 0.35$) and revealed moderate heterogeneity (Q (8.30), $df = 4$, $I^2 = 52\%$) (Fig. 6). The test for subgroup differences revealed a statistically significant difference for physical activity modality (Q (7.38), $df = 2$, $p = 0.02$, $I^2 = 73\%$).

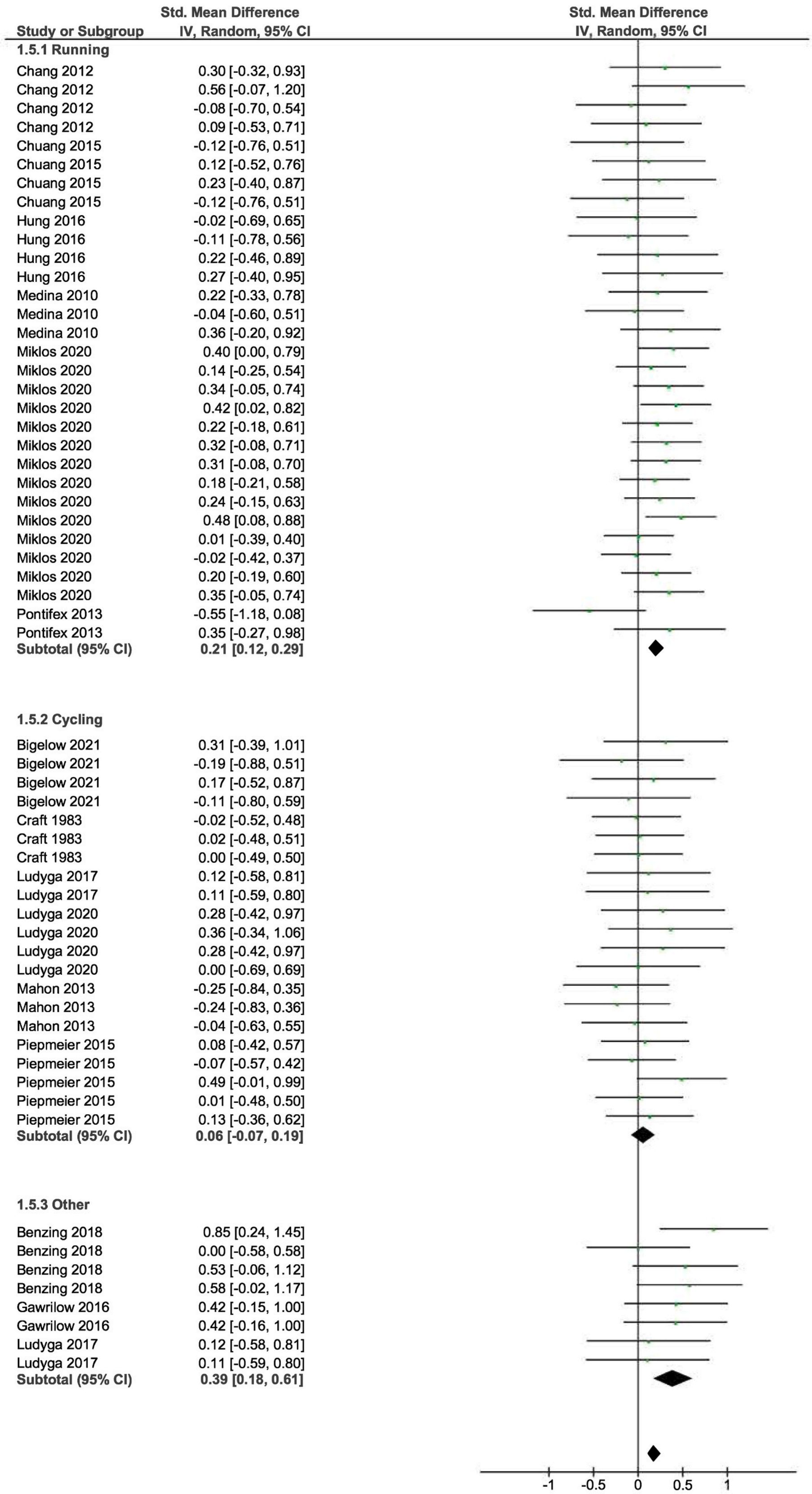

Fig. 6. *Forest plot showing sub-group analysis for modality of physical activity intervention. Note.* Running interventions (*SMD* = *0.21, p* < *0.01;* I^2 = *75%*), cycling interventions (*SMD* = *0.06, p* = *0.35;* I^2 = *52%*), and 'other' physical activity interventions (*SMD* = *0.39, p* < *0.01;* I^2 = *65%*).

2.3.7. Timing of cognitive function tasks post exercise

Finally, timing of completion of the cognitive function tests were categorised into 'immediately post-intervention', 2–10 min post-intervention' and '> 10 min post-intervention'. The results showed that studies which completed the cognitive function tasks 2–10 min post intervention had a statistically significant small effect on cognitive performance (SMD = 0.21, [0.12, 0.30], $p = < 0.01$) with a substantial heterogeneity (Q (13.32), $df = 2$, $I^2 = 86\%$). The sub-group analysis revealed that studies that completed the tests >10 min post intervention showed small positive effect on cognition, although this effect was not statistically significant (SMD = 0.19, [−0.09, 0.47], $p = 0.19$) with no heterogeneity (Q (0.74), $df = 1$, $I^2 = 0\%$). Finally, studies that completed the tasks immediately post intervention revealed a small effect on cognition, however this effect did not reach statistical significance (SMD = 0.17, [−0.01, 0.35], $p = 0.06$) but had a substantial heterogeneity (Q (16.65), $df = 3$, $I^2 = 82\%$) (see Fig. 7). The results from the test for subgroup differences were non-significant for timing of cognitive function tasks post exercise (Q (0.20), $df = 2$, $p = 0.91$, $I^2 = 0\%$).

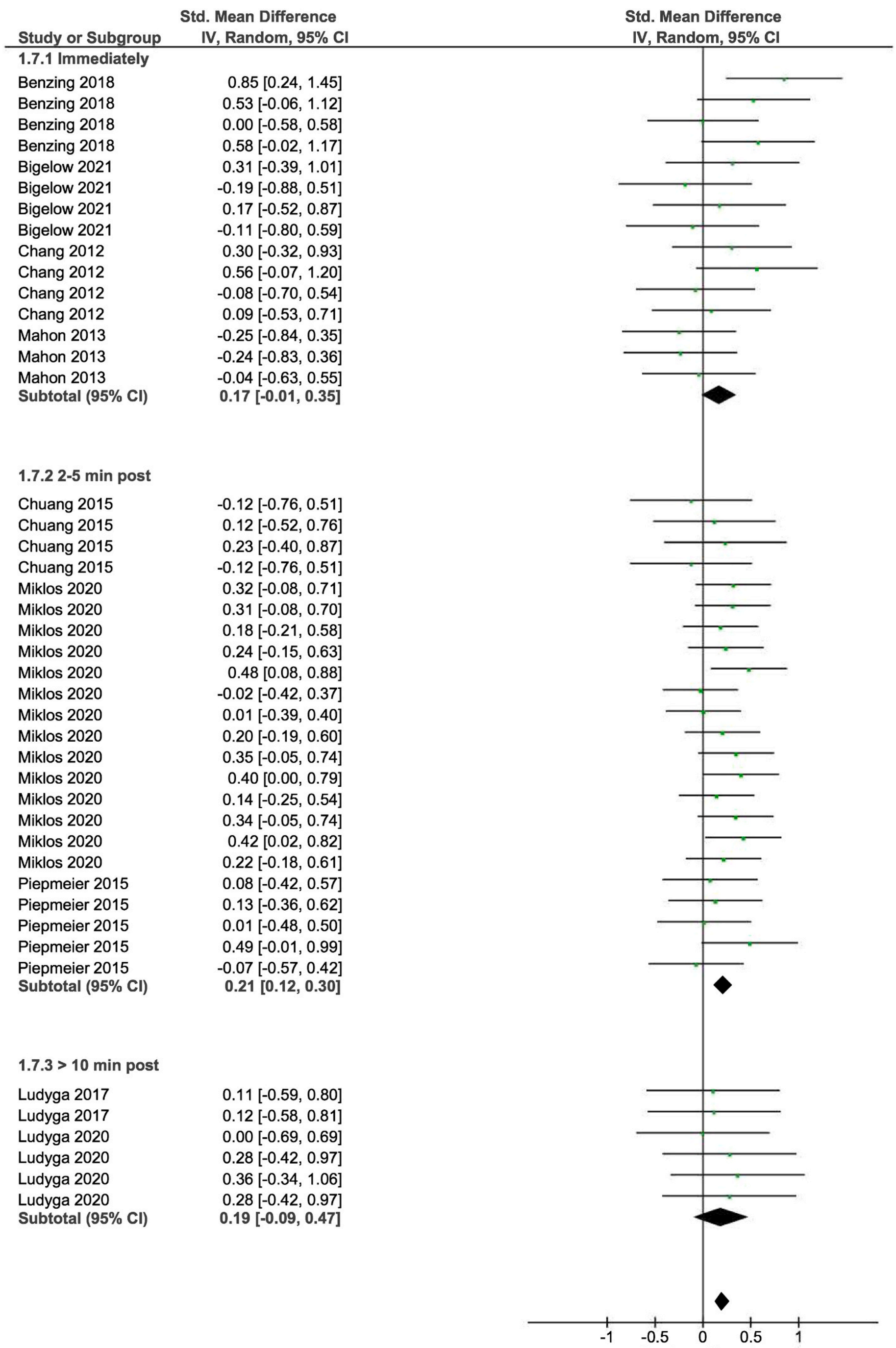

Fig. 7. *Forest plot showing sub-group analysis for timing of cognitive function test completion post-intervention. Note.* Immediately post-interventions (*SMD = 0.17, p = 0.06;* $I^2 = 82\%$), 2–5 min post-intervention (*SMD = 0.21, p < 0.01;* $I^2 = 86\%$), and >10 min post-intervention (*SMD = 0.19, p = 0.19;* $I^2 = 0\%$).

3. Discussion

The main aim of this systematic review and meta-analysis was to examine the effects of acute physical activity interventions on cognitive function in children and adolescents with ADHD. Specifically, this meta-analysis examined key moderating variables in the acute effects of physical activity on cognition in children and adolescents with ADHD, including the cognitive function domain, the physical activity duration, study design, the modality of physical activity, and the timing of cognitive function tests following physical activity. Of the 14 studies which were included in the review and meta-analysis, the overall effect showed a small benefit of acute physical activity compared to a control condition on cognitive function in children and adolescents with ADHD (SMD = 0.18). The sub-analyses revealed that acute physical activity interventions were associated with statistically significant small beneficial effects on cognitive flexibility (SMD = 0.21), attention (SMD = 0.20) and inhibitory control (SMD = 0.18); however, memory (SMD = 0.02) was not shown to be enhanced. The analysis also revealed that cognition was improved following physical activity interventions 11–20 min (SMD = 0.23) and >20 min (SMD = 0.13) in duration, whereas interventions less than 10 min in duration had no significant benefit (SMD = 0.11). Whist studies with a between subject design demonstrated a positive effect on subsequent cognition (SMD = 0.28), those studies with a within subject design did not (SMD = 0.09). With regards to the modality of physical activity, running (SMD = 0.21) and 'other' modes of physical activity including trampolining, exergaming, and coordinative tasks (SMD = 0.39) had beneficial effects on cognition, whilst cycling did not (SMD = 0.06). Finally, the positive effects of physical activity on cognition in children and adolescents with ADHD occur after a short delay of 2–10 min following the activity (SMD = 0.21); whilst small, non-statistically significant, effects were found when tests were completed immediately (SMD = 0.17) and >10 min post-intervention (SMD = 0.19). To our knowledge, this study is the first meta-analysis to investigate the effects of acute physical activity interventions on cognitive function in children and adolescents with ADHD with specific focus on key moderating variables (such as the duration and modality of activity) which influence the subsequent effects on cognition.

The present study found that, overall, acute physical activity interventions had a small beneficial effect on cognitive function in children and adolescents with ADHD (SMD = 0.18). The present meta-analysis is novel in examining the acute effects of physical activity on children and adolescents with ADHD; and builds on previous systematic reviews by adding meta-analytical results and insights. Previous reviews have investigated the combined effects of acute and chronic physical activity interventions in children and adolescents with ADHD; with one study examining both ADHD and autism (Tan, Pooley, & Speelman, 2016), and one solely focusing on chronic interventions (Welsch et al., 2021). Systematic reviews investigating the effects of acute physical activity interventions on cognitive function in children and adolescents with ADHD (Grassmann et al., 2017) have also reported beneficial effects, and therefore support the findings of the present meta-analysis.

The results of the present study are the first to demonstrate the effectiveness of acute physical activity interventions on four individual cognitive domains, namely cognitive flexibility, inhibitory control, memory, and attention. It was found that cognitive flexibility (SMD = 0.21), attention (SMD = 0.20) and inhibitory control (SMD = 0.18) had a small significant improvement following acute physical activity. However, there were no effects of acute physical activity on memory (SMD = 0.02). Silva et al. (2015) investigated the effects of an acute physical activity intervention on subsequent attention in children and adolescents with ADHD and found that both attention and impulse control were significantly improved after physical activity. It was suggested that this improvement was due to the release of serotonin, dopamine and norepinephrine which helps the participants remain focused and calm. The findings from Silva et al. (2015) support the present research and provide some evidence regarding the underpinning mechanisms for the acute effects of physical activity on attention in children and adolescents with ADHD.

Previous research has also found similar beneficial effects of a single bout of physical activity on inhibitory control in children and adolescents with ADHD, with specific increases in response accuracy (Yu et al., 2020). Specifically, these beneficial effects were reported 30 and 60 min post-physical activity (Yu et al., 2020). Finally, cognitive flexibility has been shown to improve following chronic physical activity interventions in children and adolescents with ADHD, with improvements in reaction times reported (Benzing & Schmidt, 2019). Although the research investigating the effects of acute physical activity on cognitive flexibility is relatively limited, evidence from the present meta-analysis and previous research exploring chronic interventions provides evidence that this important cognitive domain can be enhanced following physical activity (Welsch et al., 2021).

Memory was the only cognitive domain not found to be improved following acute physical activity (SMD = 0.02). This could be due to only a small number of studies investigating memory as a cognitive domain (3 studies, yielding 5 effect sizes). Although the present meta-analysis provides evidence of no overall effect of physical activity on memory in children and adolescents with ADHD, the study of Bigelow et al. (2021) found a small beneficial effect. The research by Bigelow et al. (2021) used a physical activity intervention lasting 10 min, a duration which the present meta-analysis revealed to be non-significant in producing a beneficial effect on cognition. It is therefore surprising that Bigelow et al. (2021) found a small beneficial effect on memory and could raise questions about whether different durations of physical activity may have different effects on each domain of cognitive function; yet this has not been investigated to date.

Moderating variables that could potentially influence the effect of acute physical activity interventions on cognition in children and adolescents with ADHD were investigated in the present meta-analysis. The first of these variables was the duration of physical activity. The present study revealed that physical activity interventions ≤10 min in duration did not benefit cognition (SMD = 0.11) compared to studies which used interventions 11–20 min (SMD = 0.23) and >20 min (SMD = 0.13) in duration. This finding has been supported by a recent review in neurotypical children and adolescents where it was suggested that longer bouts of physical activity have a greater benefit on cognition compared to shorter durations (Williams et al., 2019). The dose-response relationship of physical activity duration and cognitive function is still relatively under-researched in children and adolescents with ADHD. The research by Craft (1983), included in the present review, was the only study to investigate different durations of acute physical activity, however it is suspected that the durations selected by Craft (1983) (1, 5 and 10 min) were too short to produce any significant benefit on cognition (Grassmann et al., 2017). Physical activity duration is thus a critical aspect of creating an effective intervention. The findings of the present study suggest that physical activity interventions >11 min in duration positively enhance subsequent cognition; an important novel finding with important implications for future intervention design.

Study design was also investigated, and it was found that studies which adopted a between subject study design demonstrated enhanced cognition following physical activity (SMD = 0.28), whereas those which used a within subject study design did not (SMD = 0.09). Although between subject designs reduce the risk of a demand effect (Charness, Gneezy, & Kuhn, 2012), it is still desired that the participants are randomly allocated to each condition. Randomization was conducted in all studies which used a between-subject deign. Two of the studies, however, did not clarify on their concealment process prior to assignment to interventions (Bigelow et al., 2021; Miklós et al., 2020) and therefore had some concerns in the risk of bias assessment. Within-subject designs measuring both pre- and post-physical activity, with effective randomization to explore the cognitive benefits following acute physical activity interventions, would be the ideal research design

(Pontifex et al., 2019). However, very few studies have used this design to date; a key limitation of the existing evidence base. The present meta-analysis adds to the current literature by acknowledging study design (between- or within-subject design) as a potential mediating variable on the effect of acute physical activity on cognition in children and adolescents with ADHD, which is an important consideration when interpreting the findings of studies in this area.

The modality of physical activity was also considered as a moderating variable in the present meta-analysis. It was found that physical activity interventions which used running (SMD = 0.21) and 'other' types of physical activity (SMD = 0.39); namely, trampolining, exergaming, and coordinative tasks as their mode of physical activity had beneficial effects on cognition in children and adolescents with ADHD, compared to those who used cycling which was found to have no effect (SMD = 0.06). It is interesting to see those interventions using more open-skills (e.g., exergaming) had a greater beneficial effect on cognition compared to closed skills. Open skill sports are activities that are influenced by the environment and often unpredictable (e.g., basketball, tennis, or martial arts); whereas closed skills are often self-paced and less influenced by environmental factors (e.g., running or cycling). Recent reviews have summarized that open-skill interventions are most beneficial to cognition (Gu, Zou, Loprinzi, Quan, & Huang, 2019; Zhu, Chen, Guo, Zhu, & Wang, 2020). This could account for the greater benefit from interventions which used trampolining, exergaming, and coordinative tasks.

A further consideration is the lack of ecological validity of interventions that used treadmill running and cycling on an ergometer, as these activities are not typical for children and adolescents in everyday situations. Evidence in neurotypical children and adolescents demonstrates a positive effect of acute games-based activities, specifically basketball interventions, on subsequent cognition (Cooper et al., 2018); however, these findings have not yet been shown in children and adolescents with ADHD. Future studies should consider including open-skill or games-based acute physical activity interventions to help identify the most beneficial type of physical activity to produce beneficial effects on cognitive function in children and adolescents with ADHD; with a particular focus on ecologically valid forms of exercise that can be incorporated into the school day.

Finally, timing of the administration of cognitive tests post physical activity was considered as a potential moderator. The results from the sub-group analysis revealed that studies administering the cognitive function tests between 2 and 10 min post-intervention had a small beneficial effect (SMD = 0.21). Small positive effects were found when tests were completed immediately following the interventions (SMD = 0.17) and >10 min post intervention (SMD = 0.19), however these did not reach statistical significance. It appears that the positive effects of physical activity in children and adolescents with ADHD occur after a short delay. Interestingly, Chang, Labban, et al. (2012) examined the effects of a delay in the administration of the cognitive function tests following physical activity in neurotypical people. Chang, Labban, et al. (2012) found benefits on cognition when cognitive tests were administered 11–20 min, and >20 min post-exercise. Therefore, findings from the broader literature in neurotypical individuals (Chang, Liu, et al., 2012) and the present meta-analysis in children and adolescents with ADHD suggest that the cognitive benefits following physical activity are greatest following a short delay of ~10 min. However, these results should be interpreted with caution, due to the limited number of studies that measure cognition at multiple timepoints following physical activity, thus these effects are potentially confounded by the other moderating variables in the physical activity-cognition relationship when comparing between studies. Alongside future studies to address this gap in the literature, in order to assist with interpretation, the timing of the cognitive tasks following physical activity should be carefully considered and accurately reported in future randomized control trials.

Further research is required as many of the moderating variables such as the cognitive domains measured, duration, study design, modality, and intensity of physical activity, alongside the timings of the measurements will ultimately combine to influence cognitive function in children and adolescents with ADHD. The current understanding of the combined influence of the moderator's relationships is limited and is therefore an important avenue for future research. However, the present meta-analysis provides important evidence of the effects of moderating variables (cognitive domain, duration of physical activity, study design, physical activity modality, and timing of cognitive tests following physical activity) and their potential to influence cognitive function following physical activity in children and adolescents with ADHD. Specifically, the results from the meta-analysis show that physical activity interventions using running, exergaming, trampolining, and coordinative tasks elicit beneficial effects on cognitive function in children and adolescents with ADHD. Secondly, the results from the sub-analysis for duration showed that interventions lasting 11–30 min in duration significantly improved subsequent cognitive function in children and adolescents with ADHD. Finally, enhancements were greatest when cognitive tasks were completed 2–10 min following physical activity.

Acute bouts of physical activity have been shown to have a small but positive effect on subsequent cognitive function in neurotypical children and adolescents (Chang, Labban, et al., 2012; Donnelly et al., 2016; Haapala, 2012; Williams et al., 2019); although moderating variables such as the modality, duration, and intensity of activity, the timing of cognitive tests post-intervention, and participant characteristics (e.g. physical fitness) influence these effects (Williams et al., 2019). However, prior to the present meta-analysis, limited research had considered these moderators in children and adolescents with ADHD. Therefore, the present meta-analysis provides novel insight to suggest that 11–30 min of moderate-vigorous physical activity, that consists of running or 'other' (e.g., coordinative) activities will elicit the greatest enhancements in cognition following physical activity in children and adolescents with ADHD.

3.1. Strengths, limitations, and future research directions

A strength of the present study is its novelty in being the first meta-analysis to be conducted investigating the effects of acute physical activity on cognitive function in children and adolescents with ADHD. Christiansen et al. (2019) highlighted this by providing evidence that no current meta-analysis has investigated the effects of acute and chronic physical activity interventions separately. Since the review by Christiansen et al. (2019), Welsch et al. (2021) published a meta-analysis investigating the effects of chronic interventions, yet there has still not been a meta-analysis with sole focus on the effects of acute physical activity interventions, highlighting the importance of the present study.

Although this study is novel in its aims and has added to the current research, there are some limitations which should be highlighted. Firstly, when there was no control intervention for one study (Craft, 1983), pre-intervention results were used as a resting control. Although this method enabled key and valuable research to be included in the present meta-analysis and review, pre-intervention results may not truly reflect a resting control condition. Secondly, due to the variability between studies, medication, sex differences, exercise intensity and comorbidities were not considered in the sub-analysis as potential covariates. The present study was unable to investigate sex differences, this was due to none of the included studies reporting the data individually for girls and boys. It would be interesting for future research to identify if physical activity affects cognition differently between the sexes. Finally, due to many of the included studies using a range of different cognitive tests, resulting in multiple outcomes, all measures were input into the meta-analysis separately. Currently there is not a standardised method of how to manage multiple outcome measures from a single study. Other studies have suggested combining effect sizes, choosing the most relevant and representative effect size, separating effect sizes into the most coherent subcategories so that effect sizes within subcategories are no longer dependent, and finally, using a multivariate meta-analysis (Fedewa & Ahn, 2011). However, issues surrounding this are the potential for high selection bias (in selecting the most relevant effect size for each study), and speed accuracy trade-offs. Therefore, in the present study, it was decided to include all outcome measures to ensure that speed-accuracy trade-offs could not affect the study outcomes, and ultimately more appropriately examine the overall effects of physical activity on subsequent cognitive performance.

3.2. Practical implications

Based upon the findings of the present meta-analysis it is recommended that, to enhance subsequent cognitive function in children and adolescents with ADHD, acute bouts of physical activity should last 11–30 min in duration. Furthermore, the current evidence base suggests that interventions using running, trampolining, exergaming, or coordinative tasks are most beneficial for subsequent cognitive function in children and adolescents with ADHD, whereas cycling was not shown to have a positive effect on cognition. It is also important to consider that the beneficial effects of an acute bout of physical activity on cognition are greatest after a short delay (2–10 min) following physical activity. These findings have the potential to be used as the basis of recommendations for the incorporation of physical activity into the daily lives of children and adolescents with ADHD; thus, may be of interest to teachers, healthcare providers and practitioners working with this population.

3.3. Conclusion

In summary, the present study is the first meta-analysis to explore the effects of acute physical activity across different domains of cognitive function in children and adolescents with ADHD, and how additional moderating variables; including the duration and modality of physical activity, study design, and the timing of cognitive function tasks following physical activity, influence these relationships. Our findings suggest that acute exercise interventions have a positive effect on cognition, with improvements in the domains of cognitive flexibility, inhibitory control, and attention. The present review recommends that future interventions last 11–30 min in duration, as this was shown to provide the greatest benefit on cognitive function in children and adolescents with ADHD. As discussed previously, the modality of physical activity also plays a key role in cognitive performance, and therefore we recommend that future studies incorporate more open-skill and games-based physical activity interventions to help in identifying the most beneficial, and ecologically valid, mode of physical activity in children and adolescents with ADHD. Finally, the delay in cognitive function task administration should be considered in future studies with suggestion that a short delay of 2–10 min elicits beneficial effects on cognition in children and adolescents with ADHD. Future research should continue to examine the time course of the acute effects of physical activity on subsequent cognition in this population, as this will be important for the implementation of future interventions, and in particular aid understanding of how physical activity could be incorporated within the school day. The research discussed in this systematic review and meta-analysis can provide some guidance on how to shape future interventions, however more research is required in order to conclude what the optimum dose of physical activity is and how physical activity could be optimally prescribed to children and adolescents with ADHD in the future.

Author note

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data available from corresponding author upon reasonable request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mhpa.2022.100469.

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