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## **CE** Is there an effective dose of aerobic exercise associated with better executive function in youth with attention deficit hyperactivity disorder?

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### ABSTRACT

Attention-deficit/hyperactivity disorder (ADHD) is the most prevalent neurodevelopmental disorder in children, and it's linked to a higher risk of academic failure, interpersonal issues, mental illness, and criminality. Despite several of the comparative and detailed reviews on the effects of ADHD interventions on core symptoms, there is no data summarizing the effects of aerobic exercise (AE) on executive functions (EFs). Therefore, this study aimed to systematically review and determine the relationship between AE (acute and chronic) dosage and EFs (attention, inhibition, set-shifting, and working memory) in youth with ADHD. The consideration of how AE dosage impacts aspects of EFs has not been investigated in detail previously. The study adhered to PRISMA guideline. Six databases were searched without any date restrictions, up to February 2021, for articles relating to AE interventions to influence EFs in youth with ADHD  $\leq 18$  years old. Quality assessment of the reviewed papers was addressed. Thirteen studies met the inclusion criteria. Improvements in all aspects of EFs were reported after children with ADHD engaged in acute AE lasting 20–30 minutes with at least moderate intensity ( $65\% \leq 80\% \text{HR}_{\text{max}}$ ). Furthermore, chronic exercise that lasts at least 45 minutes and in the range of moderate to high intensity (i.e.,  $60\% \leq 75\% \text{HR}_{\text{max}}$ ), 3 days/week for 6–12, elicits additional benefits in inhibition and set-shifting. Different dosage of AE might differently influence aspects of EFs; however, this finding rests on preliminary evidence at this stage and thus should be treated with caution. It is necessary to establish suitable interventions with regard to the dosage of AE types to improve EFs in young people with ADHD.

### ARTICLE HISTORY

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### KEYWORDS

Aerobic exercise; dosage; executive functions; ADHD; exercise prescription

Attention-deficit/hyperactivity disorder (ADHD) is one of the most prevalent neurodevelopmental disorders in children, with the worldwide figures showing a diagnosis rate of 6% to 8% (Wittchen et al., 2011). According to the Diagnostic and Statistical Manual of Mental Disorders (DSM-5), the disorder's characteristic symptoms consist of short attention span, impulsive behavior, impaired inhibition, and hyperactivity (American Psychiatric Association, 2013). In almost two-thirds of the affected children, these

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symptoms persist into adolescence and even adulthood (Fayyad et al., 2017). ADHD is known to have long-term adverse effects and is believed to be a significant contributing factor to poor educational performance (Jangmo et al., 2019), personality issues, various mental illnesses (Ditrich et al., 2021; Miller et al., 2008), and even delinquent behavior (Biederman et al., 2006; Retz et al., 2021). It is possible that these symptoms are directly or indirectly related to the executive functions (EFs) (Biederman et al., 2006), and therefore the study of this link between EFs and ADHD is of particular interest.

EFs are higher-level processes essential in purposeful and controlled behavior (Welsh & Pennington, 1988). The areas of the brain responsible for regulating EFs are mostly the prefrontal cortex and the temporal, parietal, limbic lobes, and striatum (Roth & Saykin, 2004). Core EFs are inhibition (self-control – resisting temptations and resisting acting impulsively) and interference control (selective attention), working memory, and cognitive flexibility (including creatively thinking “outside the box,” seeing anything from different perspectives, and quickly and flexibly adapting to changed circumstances) (Diamond, 2013; Miyake et al., 2000). Over the years, it has become more evident that impaired development of EFs might directly or indirectly lead to ADHD (Brown, 2002).

ADHD medication is often prescribed as the first step in treating the disorder (Pliszka, 2007; Wolraich et al., 2011). In many cases, it is useful only in managing the symptoms. However, due to the long-term side effects (Buitelaar & Medori, 2010; Dela Peña et al., 2013; Wilens et al., 2008) and a relatively high non-response rate (20–25%) (Childress & Sallee, 2014; Shyu et al., 2015; Wang et al., 2013) the use of pharmaceuticals/stimulant medication has become a controversial issue. Many prefer alternative approaches such as cognitive training, neurofeedback, behavioral therapy, diets, and combined interventions. Among the non-pharmacological treatments, exercise has also gained traction as a main line of treatment or as a complementary approach. A recent systematic review has shown that exercise has the highest average effect size (Morris  $d = 0.93$ ) on cognitive difficulties in individuals with ADHD among several non-pharmacological interventions, such as neurofeedback, cognitive-behavioral therapy, and cognitive training (Lambeze et al., 2020).

The pathophysiology of ADHD is complicated, and the difference between children with and without ADHD is signaled by neurophysiological anomalies in central nerve structures, network activity, and brain neurochemicals (Christiansen et al., 2019). Exercise may function as an endogenous stimulus, triggering a series of molecular neuroplastic processes that finally result in nervous system structural changes (Voss et al., 2013). Our ability to structure brain activity patterns, which are required for planning, initiating, and executing movements, perceiving sensory inputs, and attenuating resting-state central nervous activity characterized by default mode network activity during cognitive processing, is essential for engaging in meaningful sensorimotor interactions with our surroundings. Inability to do so is linked to a lack of attention and inhibitory control, resulting in ADHD (Uytun et al., 2017). According to evidence exercise positively affects function of default mode network activity in individuals with ADHD (Gutmann et al., 2015; Huang et al., 2018, 2017). Exercise also can positively affect current and future cognitive function via a variety of central nervous system pathways, including changes in cortical monoaminergic transmission, brain neurotrophin levels, and cerebral blood flow (Christiansen et al., 2019).

Children with ADHD are less likely than their counterparts without ADHD to fulfill prescribed levels of physical activity (Cook et al., 2015), which might be connected to impairments in not just physical capacity but also cognitive functions (Kim et al., 2011). Also, in a large sample of the general population ( $n = 45,897$ ), Cook et al. reported that children with ADHD who are not treated with medication are sedentary or are prone to be sedentary. Given the increased risk of obesity and sedentary behavior in unmedicated youth with ADHD (Cook et al., 2015), it is critical to begin a physically active lifestyle as early as childhood. Additionally, a systematic review of 58 studies, Bidzan-Bluma and Lipowska (2018) found that children's participation in physical activity is linked to changes in certain brain regions, resulting in improved memory function (working memory in particular) and cognitive control. Increased physical activity has been found to improve cognitive performance, particularly working memory, visual-spatial memory, and cognitive flexibility, independent of the children's age (early, mid, or late childhood) (Bidzan-Bluma & Lipowska, 2018). Such information might be valuable in creating pre-adolescent training programs targeted at enhancing cognitive processes, as well as guiding researchers and practitioners on the vast variety of advantages that come from physical activity.

Exercise is a form of physical activity in which muscles are used in a coordinated and controlled manner to enhance performance and improve the body's overall health and fitness (MacKay-Lyons et al., 2020). There are two major types of exercise: aerobic/endurance, such as running or walking, and resistance/strength, such as weight lifting (Wasfy & Baggish, 2016). According to a recently published systematic review, aerobic exercise (AE) has a positive effect on EFs and related disorders such as impulsive behavior (Den Heijer et al., 2017). This review focuses exclusively on AE, given the relatively well-developed concept of exercise dose-response for this modality.

Despite the significant role that AE can play in treating ADHD, its specific parameters have not been systematically investigated. Although there are various ways of measuring AE exposure, the general concepts for quantifying the exercise dose are described below (Wasfy & Baggish, 2016). To quantify AE exposure, we need to determine exercise dose, a concept comprised of three distinct variables, namely duration, frequency, and intensity of the exercise. Together their product yields the exercise dose, usually reported as kilocalories or Metabolic Equivalents (MET)-minutes per day or per week. Duration is the amount of time dedicated to a single exercise session and is expressed in minutes or hours in aerobic exercises. Frequency is the number of exercise sessions over a long period of time (days, weeks, or months). Intensity can be expressed either in absolute terms (e.g., METs, oxygen uptake (L/min) or kilocalories/min) or relative to exercise capacity (e.g.,  $\%VO_{2max}$ ,  $\%HR_{max}$ ,  $\%VO_2$  reserve,  $\%Heart Rate Reserve$  (HRR)) (Garber et al., 2011).

A recent systematic review on the influence of physical activity on young patients with ADHD reported an acute positive effect on processing speed, working memory, planning, and problem-solving associated with 20 to 30 minutes of exercises with an intensity ranging from 40 to 75% (Suarez-Manzano et al., 2018). However, this review consisted of a wide variety of exercises with anaerobic exercises included along with AE and motor skills. The problem with this approach is that it is hard to determine each exercise's dosage and their respective influence on EFs. Moreover, since then, many more studies have been published, which calls for a new systematic review to include the more recent data to form a more current understanding of AE parameters to affect EFs in young

people with ADHD. To our knowledge, no study has evaluated the dose of AE for the purpose of identifying the parameters that affect executive functions in youth with ADHD, with a goal to develop more precise exercise prescription for optimal effect. Therefore, this systematic review aims to systematically review the results of studies that have examined the effect of different AE dosage on various aspects of EFs in youth with ADHD.

## Methods

A systematic search was conducted in accordance with the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” (PRISMA) guidelines (Page et al., 2021).

### *Study eligibility criteria*

The qualitative synthesis was performed on all the studies in this review. The following criteria were used for the inclusion of a study in this review: 1) the study had an AE intervention with a clear description of AE dosage (frequency, intensity, and duration); 2) the study had measured executive functions as outcomes with valid measures, and had included pre- or – post-intervention assessment or both; 3) the study must conduct an intervention on individuals  $\leq 18$  years of age diagnosed with ADHD; 4) only articles published in English and peer-reviewed journals were considered. Books, reviews, theses, dissertations, commentaries, qualitative research, and case studies were excluded. Studies examining the effect of intervention on physiological or psychological processes unrelated to neurological function (i.e., EFs) were excluded.

### *Data sources*

Six databases – MEDLINE, Scopus, Google Scholar, EMBASE, Web of Science and ProQuest – were searched without any date restrictions, up to February 2021, for articles relating to AE intervention in children and adolescents with ADHD. The leading search group terms were: (attention deficit hyperactivity disorder OR ADHD OR attention deficit disorder) AND (children OR childhood OR school-age youth OR adolescent OR student OR primary school OR high school OR young adult OR adult OR college student OR adulthood) AND (exercise OR physical exercise OR aerobic exercise OR cardio exercise OR cardiovascular exercise OR exercise training OR aerobic training OR physical activity OR sensorimotor training) AND (executive functions OR cognitive function OR inhibitory control OR working memory OR cognitive flexibility OR task switching OR cognitive control OR attention) AND (intervention OR program OR study OR trial).

### *Study selection and extraction*

Two disciplinary-specific reviewers with systematic review experience worked independently to screen the studies’ title and abstract for relevance to the review. According to the criteria mentioned above, the authors searched relevant full-text articles and evaluated the studies for inclusion considerations. The reference lists of the included studies and other

relevant systematic reviews were also reviewed for potential papers. In instances of disagreements over the inclusion of individual research or the specific data obtained, the matter was resolved through discussion with a third disciplinary-specific reviewer. Reviewers extracted data from each included study, including details of the methodology, sample characteristics, intervention components, type of AE (acute and chronic and their modalities) and its characteristics (duration, frequency, and intensity), outcomes, executive functions assessed, and the statistically significant intervention effects. In the literature on exercise science, “chronic AE” intervention is defined as a series of bouts of exercise over a short or long period of time, whereas “acute AE” is described as a single bout of exercise (Riebe et al., 2018; Sellami et al., 2018). All types of exercises that raise heart rate and oxygen usage and are performed for a long period of time, such as (treadmill) running, (ergometer) cycling, swimming, and jumping, were included in AE.

### **Quality assessment**

Two authors independently assessed the quality of the included studies. Quality of evidence was evaluated based on the Physiotherapy Evidence Database (PEDro) scale. This scale has been reported to be valid and reliable (De Morton, 2009; Page et al., 2021). For the purpose of this study, the modified version of PEDro was used (Ludyga et al., 2016), this criteria identified as relevant to the current review have previously been used to review a similar area (Ludyga et al., 2016) and has the following items: eligibility criteria, random allocation, concealed allocation, baseline comparability, reporting and control of exercise loads, blinded assessors, incomplete outcome data, intervention as allocated, between-group or condition analysis, as well as both point estimates and measures of variability. Each item on the scale was evaluated as “explicitly described and present” (✓), “absent” (x) or “unclear or inadequately described” (?). Similar to the process described for the study selection, the level of agreement between raters was calculated on a dichotomous scale (✓ = 1 vs x or ? = 0), using percentage agreement and Cohen’s Kappa (Higgins et al., 2019). Depending on the study design, some items were coded as not applicable (N/A) and not included in agreement calculations. Detailed information about all the studies is presented in Table 3. Interrater reliability metrics for the quality assessments indicated substantial agreement for all items (percentage agreement 95%,  $k = 0.81$ ).

### **Results**

The search strategy identified 1,442 potentially relevant articles, of which 1393 were removed because of duplicates, other languages, and interventions other than physical activity. Following screening and detailed assessment, further 36 articles were excluded for different reasons (e.g., no dose description, full text unavailable, study design). Therefore, 13 studies were deemed suitable for this systematic review (Figure 1).

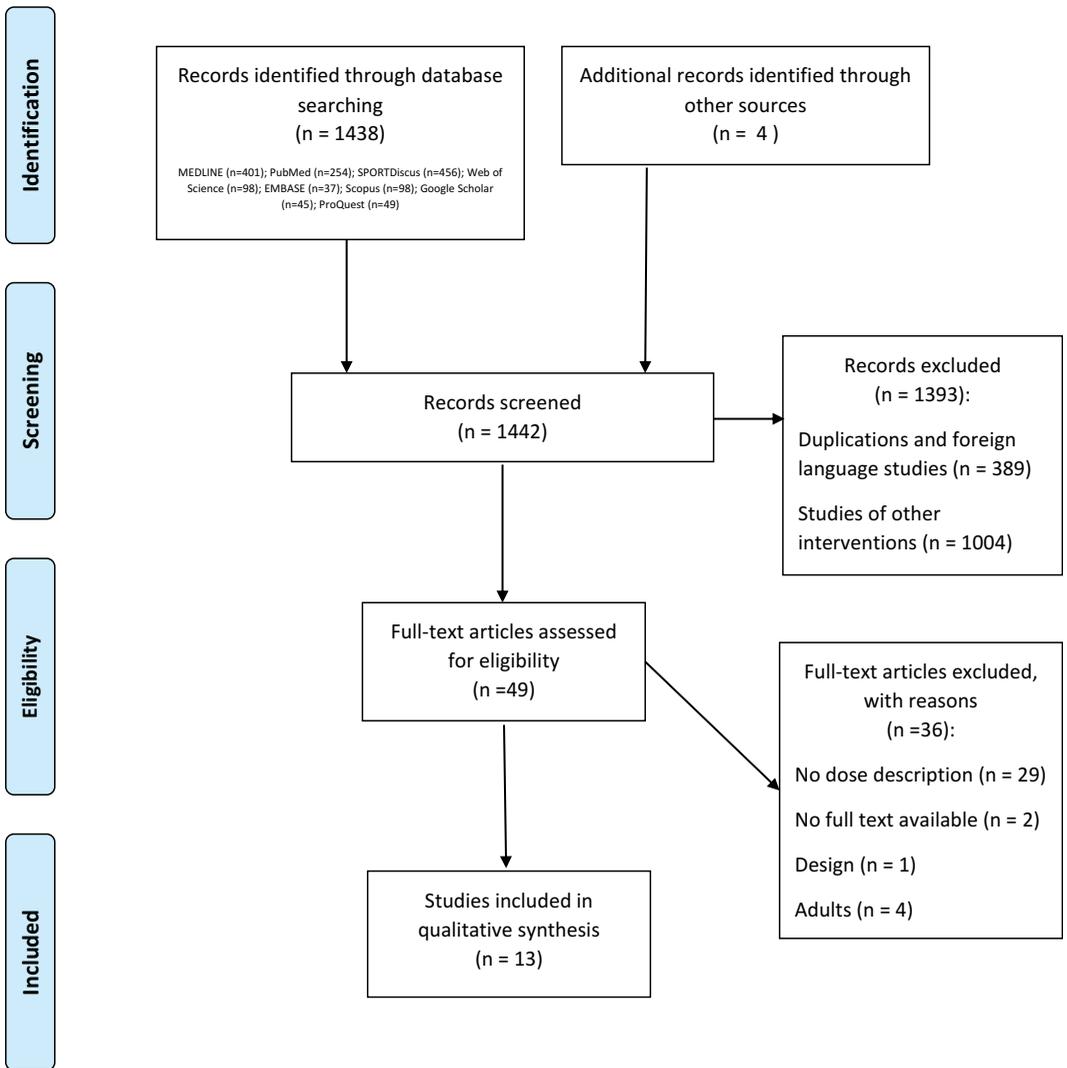


Figure 1. PRISMA flowchart of the study.

### Overview of studies

All 13 studies included (Figure 1) were published between 2012 and 2020 (Chang et al., 2012; Choi et al., 2015; Chuang et al., 2015; Durgut et al., 2020; Geladé et al., 2017; Hung et al., 2016; Lee et al., 2017; Liberati et al., 2009; Ludyga et al., 2017, 2020; Mahon et al., 2013; Miklós et al., 2020; Piepmeier et al., 2015; Pontifex et al., 2013). The included studies reflected an age range of 6–18 years old.

This review included data from 610 individuals, and the sample size of the studies varied from 12 (Lee et al., 2017) to 150 (Miklós et al., 2020) participants. Across the 13 studies, three were conducted in the USA (Mahon et al., 2013; Piepmeier et al., 2015; Pontifex et al., 2013), two in China (Chang et al., 2012; Chuang et al., 2015), Switzerland

(Ludyga et al., 2017, 2020) and South Korea (Choi et al., 2015; Lee et al., 2017), and a single study each from Taiwan (Hung et al., 2016), Hungary (Miklós et al., 2020), Turkey (Durgut et al., 2020) and the Netherlands (Geladé et al., 2017). All studies had AE intervention, of which nine studies (70%) were with acute AE intervention (Chang et al., 2012; Chuang et al., 2015; Hung et al., 2016; Ludyga et al., 2017, 2020; Mahon et al., 2013; Miklós et al., 2020; Piepmeier et al., 2015; Pontifex et al., 2013), and four studies (30%) were with chronic AE intervention (Choi et al., 2015; Durgut et al., 2020; Geladé et al., 2017; Lee et al., 2017).

Seven of the 13 studies used a cross-over design with pre and posttest design (Chuang et al., 2015; Hung et al., 2016; Ludyga et al., 2017, 2020; Mahon et al., 2013; Piepmeier et al., 2015; Pontifex et al., 2013), and one used a posttest only design (i.e., no pretest) (Pontifex et al., 2013); three were matched pairs experiment (pre-post design) (Choi et al., 2015; Lee et al., 2017; Miklós et al., 2020) and three were randomized controlled trials (Chang et al., 2012; Durgut et al., 2020; Geladé et al., 2017). Detailed information about all the studies is presented in Tables 1–3.

### **Assessment of executive functions**

Of the 13 studies included, five measured inhibition (Chuang et al., 2015; Durgut et al., 2020; Lee et al., 2017; Ludyga et al., 2017; Pontifex et al., 2013), three set-shifting (Choi et al., 2015; Hung et al., 2016; Ludyga et al., 2020) and one attention (Mahon et al., 2013). Four studies assessed more than one aspect of EF, including inhibition and attention (Miklós et al., 2020), inhibition and set-shifting (Chang et al., 2012), inhibition, set-shifting and problem solving (Piepmeier et al., 2015), and inhibition, working memory, and attention (Geladé et al., 2017) each.

### **Aerobic exercise dosage**

Duration of every single bout of acute AE was either 20 minutes (Ludyga et al., 2017, 2020; Mahon et al., 2013; Miklós et al., 2020; Piepmeier et al., 2015; Pontifex et al., 2013) or 30 minutes (Chang et al., 2012; Chuang et al., 2015; Hung et al., 2016). For the purposes of this study we used the criteria of (Norton et al., 2010) to categorize the intensity of physical activity. According to Norton et al. (2010), p. 3 < 6 MET,  $55 < 70\%$   $HR_{max}$ ,  $40 < 60\%$  HRR,  $40 < 60\%$   $VO_{2max}$ , or 11–13 Borg Rating of Perceived Exertion (RPE) (6–20)/3–4 RPE (0–10) is categorized as moderate intensity;  $6 < 9$  MET,  $70 < 90\%$   $HR_{max}$ ,  $60 < 85\%$  HRR,  $60 < 85\%$   $VO_{2max}$  or 14–15 RPE (6–20)/5–6 RPE (0–10) is defined as vigorous intensity; and;  $6 < 9$  MET,  $70 < 90\%$   $HR_{max}$ ,  $60 < 85\%$  HRR,  $60 < 85\%$   $VO_{2max}$  or 14–15 RPE (6–20)/5–6 RPE (0–10); and  $\geq 9$  MET,  $\geq 90\%$   $HR_{max}$ ,  $\geq 85\%$  HRR,  $\geq 85\%$   $VO_{2max}$  or  $\geq 17$  RPE (6–20)/  $\geq 7$  RPE (0–10) is corresponded to high intensity of AE (Norton et al., 2010). Of the nine studies of an acute bout of AE included, the majority (6 of 9) were of moderate to vigorous intensity AE (Chang et al., 2012; Hung et al., 2016; Ludyga et al., 2017, 2020; Miklós et al., 2020; Pontifex et al., 2013); one single study reported on moderate intensity (Chuang et al., 2015), one vigorous (Piepmeier et al., 2015) and one high (Mahon et al., 2013) each.



**Table 1.** Characteristics of included studies assessed effects of acute aerobic exercise on executive functions.

Study Author(s) (year, country/ region)	Acute Aerobic Exercise intervention components						Post intervention tests	
	Sample (number, medication status/ age/year)	ADHD type	Content of intervention (condition for the control if applicable)	Dose description		Executive function assessed		
				Duration (min)	Intensity			Design
Chang et al. (2012, China)	Children (8–13 years old; medicated & non- medicated) ADHD children; 40)	Mixed (all types)	INT: Running on a treadmill (warm up for 5 min, main exercise for 20 min, and cool down for 5 min) CON: to watch a running/ exercise- related video for the same duration as the exercise group	30	50%–70% HRR	RCT	Stroop Test; Wisconsin Card Sorting Test	Stroop Test: For both Stroop/Word and Stroop Color, there was a significant main effect of time, where shorter times were observed in the posttest. However, main effects for group and the interaction of group by time were not significant. For Stroop Color-Word, there was a significant main effect of time and an interaction of group by time. Shorter durations of both groups were found in the posttest compared with the pretest, the duration than those in the control group. WCST: For both Non-perseverative Errors and Categories Completed there was a significant main effect of time and an interaction of group by time. Simple effect result showed that a significant time effect was found for the exercise group, but not for the control group. For Total Correct, Perseverative Responses, Perseverative Errors, and Conceptual Level Response there was a significant main effect of time, and better performances were found in the posttest compared with the pretest.
Chuang et al. (2015, China)	Children (8–12 years old, medication discontinued 24 h before, 19)	Mixed (all types)	INT: 30-min treadmill exercise and 30-min video- watching	30	60% of HRR	Cross-over	Go/No Go Task	Inhibition  The mean reaction time (RT) for Go stimuli was shorter in the exercise session than that in the video watching session. No differences in terms of hit rate, omission error rate, or commission error rate were revealed between exercise and video-watching sessions.

(Continued)

Table 1. (Continued).

		Acute Aerobic Exercise intervention components							
Study Author(s) (year, country/ region)	Sample (number, medication statuses age/year)	ADHD type	Dose description		Design	Executive functions test Paradigm	Executive function assessed	Post intervention tests	
			Content of intervention (condition for the control if applicable)	Duration (min)					Intensity
Hung et al.(2016, Taiwan)	Children (8–12 years old, ADHD (medication discontinued 24 h before) & healthy children,; 36)	Mixed (all types)	INT: Aerobic exercise session (including 5 min of warming up, 20 min of main exercise on treadmill, and 5 min of cooling down) CON: Resting session (reading while seated)	30	50–70% HRR	Cross-over	Task Switching Paradigm	Set-shifting	Global switch: For RT, as significantSession (post-exercise, post-resting) by Condition (Pure and mixed) interaction was found. Participants responded faster in the pure condition than in the mixed condition both post-exercise and post-resting. For response accuracy, there was no significant main effect of session or interaction. Local switch: For RT, there was no main effect of session or interaction. For response accuracy, not significant result was found. Global and local switch costs: As for RT, there were significant differences in global switch costs between post-resting and post-exercise sessions. However, no significant differences in local switch costs were observed. Both groups (AE and control) showed higher cognitive flexibility following AE. Effects for condition were obtained for category, fluency, and originality. These effects indicated higher scores following AE group compared with the control condition
Ludyga et al. (2020, Switzerland)	Adolescents (11–16 years old, medicated ADHD & healthy children, 36)	Combined	INT: ADHD group: Aerobic exercise (20 mins cycling bout on an ergometer) CON: physically inactive control condition (20 mins watching a Video)	20	65% to 70% HR <sub>max</sub>	Cross-over	Alternate Uses Task	Set-shifting	

(Continued)



Table 1. (Continued).

Study Author(s) (year, country/ region)	Sample (number, medication statuses age/year)	ADHD type	Acute Aerobic Exercise intervention components				Executive functions test	Executive function assessed	Post intervention tests	
			Content of intervention (condition for the control if applicable)	Dose description		Design				Executive functions test
				Duration (min)	Intensity					
Ludyga et al. (2017, Switzerland)	Adolescents (11–16 years old, medicated ADHD, 36)	Combined	INT: Aerobic exercise (20 mins cycling bout on an ergometer), physically inactive control condition (20 mins watching a Video) and coordinative exercise (20 min object control skills and bilateral coordination of lower and upper extremities)	20	65% to 70% HR <sub>max</sub>	Cross-over	Modified Flanker Task	Inhibition	There was a significant interaction of time and condition for RT, indicating a greater decrease of RT following exercise compared to watching a video in both groups. No such interaction was observed for accuracy. A time by condition (AE, coordinative exercise, control) interaction for RT in children with ADHD was found, indicating that AE led to a greater reduction of RT than coordinative exercise. In healthy comparisons, exercise-induced changes in RT were not significantly different between the two exercise modalities.	

(Continued)

Table 1. (Continued).

		Acute Aerobic Exercise intervention components			
Study Author(s) (year, country/ region)	Sample (number, medication statuses age/year)	ADHD type	Dose description		Executive function assessed
			Content of intervention (condition for the control if applicable)	Duration (min)	
Mahon et al. (2013, USA)	Children (8–14 years old, ADHD (with medication and without medication (medication discontinued 18–24 before) & healthy children, 42)	N.A.	INT: 3 min warm- up, 20 exercise on electrically- braked cycle ergometer; 30 sec high intensity exercise/ 30 sec rest; 10 min exercise totally)	20	Attention
				Intensity 90% of peak aerobic work rate	Executive functions test Continuous Performance Task & Behavior Assessment System for Children (hyperactivity and attention subscales)
				Design Cross over	Post intervention tests
					There was a significant increase in the error of omission t-score over time (pre to post exercise). There were no significant findings for the error of commission-score. In the ADHD group the reaction time score was significantly higher than children without ADHD, significantly decreased with medication, and significantly increased over time.

(Continued)



Table 1. (Continued).

Study Author(s) (year, country/ region)	Sample (number, medication statuses age/year)	ADHD type	Acute Aerobic Exercise intervention components				Executive function assessed	Post intervention tests
			Content of intervention (condition for the control if applicable)	Dose description Duration (min)	Intensity	Design		
Miklós et al. (2020, Hungary)	Children (6–12 years old, medicated & non- medicated ADHD, healthy children, 150)	Mixed (all types)	INT: physical activity session (running activity), while watching a cartoon video: the total time of 20 min was divided into 4 × 4 periods, with 1-min slow walking “breaks” between each period. CON: watching a cartoon video while seated	20	60–80%HR <sub>max</sub>	Pre-post	Executive functions test Test Battery for Attention Testing for Children (KITAP): alertness, distraction, divided attention, flexibility, and go/no-go	AE group compared to control group (video watching condition) had a significantly positive influence on 2 out of 15 measured parameters (median RT in the alertness task and error rates in the divided attention task) for the medicated group and on 2 out of the 15 measured variables (number of total errors and errors when distractor was presented, both in the distractibility task) regarding the treatment-naïve group
Piepmeier et al. (2015, USA)	Adolescents (10.75 ± 2.27, medicated ADHD & healthy children, 32)	Mixed (all types)	INT: aerobic exercise (a 5-min warm- up, 20 min of cycling on a Recumbent Cycle- Ergometer, and a 5-min cool-down) CON: or watching a nature documentary	20	5–7 RPE (0– 10 OMNI scale)	Cross-over	Stroop Test, Tower of London & Trail Making Test	Inhibition, Problem solving & Set- shifting  Stroop Test: participants used less time to complete the test in the exercise condition. Follow-up analyses showed that participants used significantly less time to complete part A (Word) and part B (Color).  Tower of London: neither the main effects for ADHD diagnosis nor condition nor the interaction between ADHD diagnosis and condition reached statistical significance. Trail Making Test: no significant difference was found between exercise and control group.

(Continued)

Table 1. (Continued).

Study Author(s) (year, country/ region)	Sample (number, medication statuses age/year)	ADHD type	Content of intervention (condition for the control if applicable)	Acute Aerobic Exercise intervention components			Executive function assessed	Post intervention tests
				Design	Dose description	Executive functions test		
Pontifex et al. (2013, USA)	Children (8–12, healthy children(N. A.), 40)	Mixed (all types)	INT: aerobic exercise on a motor- driven treadmill CON: seated reading	Cross-over	20 65% and 75% HR <sub>max</sub>	Flanker Task with a Compumedics Neuroscan	Inhibition	Both groups exhibited greater response accuracy and stimulus-related processing, with the children with ADHD also exhibiting selective enhancements in regulatory processes, compared with after a similar duration of seated reading. For RT, Analysis of median RT for trials immediately following an error revealed greater posterior slowing following the exercise condition relative to following the reading condition only for children with ADHD For accuracy, both groups exhibited greater response accuracy relative to following reading.

Note: HR (Heart Rate); HR max (maximal Heart Rate); HRR (Heart Rate Reserve); RPE (Rating of Perceived Exertion); RT: Reaction Time; N.A.: not available



**Table 2.** Characteristics of included studies assessed effects of chronic aerobic exercise on executive functions.

Study Author(s) (years, country/ region)	Sample (number, status/ age/year)	ADHD type	Content of intervention (condition for the control if applicable)	Chronic Aerobic Exercise intervention components				Executive function test	Executive function assessed	Post intervention tests Immediate Follow-up (duration)
				Frequency	Duration	Intensity	Design			
Choi et al. (2015, South Korea)	Adolescents (13– 18 years old; medicated ADHD, healthy adolescents 30)	N.A.	INT1: sports-ADHD (10 min for stretching and warming up, 60 min for aerobic exercise, and 10 min for feedback and cooling down) Aerobic exercises consisted of running (shuttle run, zigzag run), jumping rope (individual and group jumps), and basketball (dribble, pass, shoot, and game) INT2: edu-ADHD: education sessions for behavior and control such as good behavior and bad behavior and interaction with family (50 min.; several days a week) CON: nophysical exercise	90 min x 3 days/w	6 w	60% HR <sub>max</sub>	Pre- post	Wisconsin Card Sorting Test (WCST)	Set-shifting	Perseverative errors decreased in the exercise group and not in the education group

(Continued)

Table 2. (Continued).

Study Author(s) (years, country/ region)	Sample (number, status age/year)	ADHD type	Content of intervention (condition for the control if applicable)	Dose description			Executive function test	Executive function assessed	Post intervention tests Immediate Follow-up (duration)
				Frequency	Duration	Intensity			
Durgut et al. (2020, Turkey)	Children (7–11 years old.(N. A.), 30)	Mixed (all types)	INT1: TT group: treadmill training (10 min of warm-up, 25 min of moderate intensity walking and 10 min of cool- down period) INT2: TT + WBVT group: treadmill training + whole body vibration training (15 mins)	INT1: 45 min x 3 days/ w INT2: 45 min + 15 min x 3 days/w	8 w	65% to 75% HR <sub>max</sub>	Stroop Test TBAG version; Behavior rating inventory of executive function (BRIEF)	Inhibition	All assessment results significantly improved in both groups at the end of the program compared to baseline values. There were significant differences between groups regarding improvements BRIEF-Teacher form in favor of the TT +WBVT group.

(Continued)



Table 2. (Continued).

Study Author(s) (years, country/ region)	Sample (number, status age/year)	ADHD type	Chronic Aerobic Exercise intervention components				Executive function test	Executive function assessed	Post intervention tests Immediate Follow-up (duration)	
			Content of intervention (condition for the control if applicable)	Frequency	Duration	Intensity				Design
Lee et al. (2017, South Korea)	Children (~9 years old, ADHD (non- medicated) children, 12)	N.A.	INT: Combined Exercise Group (10 m warm- up, 40 m main exercise, and 10 m cool down) CON: N.A.	60 min x 3 days/w	12 w	45–75% of HRR and 11–16 RPE	Pre- post	Stroop Color and Word Test	Inhibition	The Color-Word Scores of the exercise group increased significantly after the 12 week session. The scores of the no- exercisegroup also increased significantly. The Interference Score of the exercise group increased after the 12 week session. The score decreased in the no-exercise group. However, the changes were not statistically significant in either group. No statistically significant differences were found between the groups for the Color-Word Score or Interference Score.

(Continued)

Table 2. (Continued).

Study Author(s) (years, country/ region)	Sample (number, status age/year)	ADHD type	Chronic Aerobic Exercise intervention components		Executive function test	Executive function assessed	Post intervention tests Immediate Follow-up (duration)
			Content of intervention (condition for the control if applicable)	Dose description			
Geladé et al. (2017, Netherlands)	Children (7–13 years old, INT3 (N.A.), 112)	N.A.	INT1: Neurofeedback (NFB) INT2: optimally titrated methylphenidate (MPH) INT3: a semi-active control intervention (PA): 5 min of warming up, 5 x 2-min vigorous intensity exercises (70–80% of HR max) 5-min break 5 x 2-min vigorous intensity exercises (80–100% of HRmax) 5-min cool down.	Frequency 45 min x 3 days/w Duration 10–12 w Intensity 70–80% HR <sub>max</sub> 80– 100% HR <sub>max</sub>	Design RCT	Inhibition, Working memory & Attention	Result showed improved attention for MPH compared to NFB and PA, as reflected by decreased response speed during the oddball task, as well as improved inhibition, impulsivity and attention, as reflected by faster stop signal reaction times, lower commission and omission error rates during the stop signal task For attention, results indicate equal improvements in all groups, with faster reaction times and less variable response speed at post- intervention compared to pre- intervention. Working memory improved over time, irrespective of received Treatment.

Note: HR (Heart Rate); HR max (maximum Heart Rate); HRR (Heart Rate Reserve); RPE (Rating of Perceived Exertion); RT: Reaction Time; N.A.: not available



Table 3. Quality assessment.

Authors	Eligibility criteria	Random allocation	Concealed allocation	Baseline comparability	Reporting and control of exercise loads	Blinded assessors	Outcome measures obtained from >85% subjects	Intervention as allocated	Between-group or condition analysis	Point estimates and measures of variability
Chang et al. (2012)	✓	✓	?	✓	✓	?	✓	✓	✓	✓
Choi et al. (2015)	✓	✓	?	✓	✓	?	✓	✓	✓	X
Chuang et al. (2015)	✓	✓	?	✓	✓	?	✓	✓	✓	✓
Durgut et al. (2020)	✓	✓	?	✓	✓	?	✓	✓	✓	X
Fritz & O'Connor (2016)	✓	✓	?	✓	✓	?	✓	✓	✓	✓
Gapin et al. (2015)	✓	NA	?	✓	✓	?	✓	✓	✓	✓
Geladé et al. (2017)	✓	✓	?	✓	✓	✓	✓	✓	✓	✓
Hung et al. (2016)	✓	NA	?	✓	✓	?	✓	✓	✓	✓
Lee et al. (2017)	X	✓	?	✓	✓	?	X	✓	✓	X
Ludyga et al. (2017)	✓	✓	?	✓	✓	?	✓	✓	✓	✓
Ludyga et al. (2020)	✓	✓	?	✓	✓	?	✓	✓	✓	✓
Mahon et al. (2013)	X	NA	?	✓	✓	✓	✓	✓	✓	X
Mehren et al. (2019a)	✓	NA	?	✓	✓	?	✓	✓	✓	X
Mehren et al. (2019b)	✓	NA	?	✓	✓	?	✓	✓	✓	X
Miklós et al. (2020)	✓	NA	?	✓	✓	X	✓	✓	✓	X
Piepmeyer et al. (2015)	X	✓	?	✓	✓	?	✓	✓	✓	✓
Pontfex et al. (2013)	✓	✓	?	✓	✓	?	✓	✓	✓	✓

Note: ✓, explicitly described and present; X absent; ? unclear or inadequately described; N/A, not applicable because of study design.

For chronic AE, the frequency ranged from 20 minutes (Geladé et al., 2017) to 90 minutes (Choi et al., 2015) per session and all met 3 sessions per week. The interventions lasted from 6 (Choi et al., 2015) to 12 (Geladé et al., 2017; Lee et al., 2017) weeks. Three of the four studies reported on the effects of moderate to vigorous intensity of AE (Choi et al., 2015; Durgut et al., 2020; Lee et al., 2017); only one single study reported vigorous and high intensity of AE (Geladé et al., 2017).

### *Acute effect of aerobic exercise on executive functions*

Of the nine identified acute AE interventions, results observed that an intervention of 20–30 minutes with at least moderate intensity (50–70% HRR, 65%–75%  $HR_{max}$ , or 5–7 RPE (0–10)) led to positive changes in inhibition aspect of EFs (Chang et al., 2012; Chuang et al., 2015; Ludyga et al., 2017; Piepmeier et al., 2015; Pontifex et al., 2013). In the post test research design by Pontifex et al. (2013), a difference in inhibition was observed across groups in the study which was in favor of the AE intervention group. However, in contrast to the studies mentioned above, the study of Miklós et al. (2020), reported no reduction in reaction time after 20 minutes of exercise at moderate to vigorous intensity (60–80%  $HR_{max}$ ).

For set-shifting, results showed a significant increase in the speed of reaction and/or the precision of response after an intervention of 20–30 minutes at a moderate to vigorous intensity (50–70% HRR, 65%–80%  $HR_{max}$ ) (Chang et al., 2012; Hung et al., 2016; Ludyga et al., 2020; Miklós et al., 2020). Results of one study also indicated that high-intensity AE negatively impacted attention and resulted in a significant increase in errors (Mahon et al., 2013), while Miklós et al. (2020) reported that 20 minutes of AE at moderate to vigorous intensity (65%–80%  $HR_{max}$ ) had a significant positive influence on some measured parameters of attention, such as alertness task and distractibility task (Miklós et al., 2020). No result was reported for the effect of acute AE on working memory of children with ADHD.

### *Chronic effects of aerobic exercise on executive functions*

The four identified chronic AE interventions showed that a minimum of 45 minutes of moderate to vigorous AE (65% to 75%  $HR_{max}$ , 45–75% of HRR) on three days per week for 8–12 weeks resulted in positive changes in inhibition aspects of EFs (Durgut et al., 2020; Lee et al., 2017); however, no positive outcome was reported in inhibition with vigorous (70–80%  $HR_{max}$ ) and high (80–100%  $HR_{max}$ ) intensity of similar duration and frequency reported in previous studies (Geladé et al., 2017). Choi et al. (2015) reported that 90 minutes of moderate intensity exercise on three days/week for six weeks led to positive changes in set-shifting by increasing the precision of response in the exercise group compared to the control group (Choi et al., 2015). Also, Geladé et al. (2017) showed that vigorous or high intensity of AE for 45 minutes on 3 days/week for 10–12 weeks increased working memory and attention of participants with ADHD from pretest to posttest (Geladé et al., 2017).

## Discussion

This systematic review aimed to determine the relationship between AE dosage and EFs in youth with ADHD. In general, the reviewed studies show that AE has a favorable influence on EFs. The advantages of exercise for certain aspects of EFs appear to be dose-dependent, and the evidence for a dose–response relationship between types of AE (acute vs. chronic) and EFs can be characterized as follows.

### *Acute AE and dose-response*

A qualitative synthesizing of the studies showed that intensity of acute AE session influences the magnitude of benefits; exercise-induced improvements of the inhibition, set-shifting, and attention aspect of EFs were mostly consistent across studies, such that 20–30 minutes of acute AE with at least moderate intensity ( $65\% \leq 80\% \text{HR}_{\text{max}}$ ) leads to improvement in inhibition and set-shifting. However, the benefits of acute AE for attention appear to be limited to moderate to vigorous-intensity; greater intensity was found to negatively influence attention. Given that only two included studies examined the effect of the acute effect of exercise on attention, this finding should be treated with caution.

Possible underlying mechanisms of EFs improvements following (at least) moderate intensity of AE in children with and without ADHD have rarely been studied. Consequently, it remains unclear whether or not the links between EFs, brain plasticity, and exercise which is found in healthy adults (Erickson et al., 2015; Kleinloog et al., 2019) exists in children and adolescents. Studies point toward a mechanism of the observed changes in EFs effects associated with moderate AE may be explained by nutritional environment it creates; indeed, exercise increases the availability and the supply of energetic substances to the brain (Doherty & Forés Miravalles, 2019). These metabolic alterations might therefore elicit a temporary normalization of the hypoactivation and hypoperfusion of the prefrontal cortex (PFC) such as is evident in children with ADHD. Interestingly, exercise has been shown to increase catecholamine expression, with an exponential increase in concentration occurring when the individual trains above the anaerobic threshold (Messan et al., 2017; Zouhal et al., 2008). Whereas, a low to moderate release of dopamine and norepinephrine is related to improvements in working memory, inhibition, and attention regulation; a higher expression of these neurotransmitters impairs EFs (Arnsten & Li, 2005; Cai & Arnsten, 1997). If moderate AE triggers a similar release of dopamine and norepinephrine in children with ADHD, the hypocatecholaminergic state's facilitation might partly explain exercise-induced benefits for EFs. Also, high-intensity AE might lead to a higher expression of neurotransmitters which reduces attention due to severe neural traffic; however, evidence lacks to support the relationship between exercise intensity and magnitude of neurotransmitter release.

### *Chronic AE and dose-response*

Our findings indicated that chronic AE of at least 45 minutes, three days/week for 6–12 weeks least moderate (i.e.,  $60\% \leq 75\% \text{HR}_{\text{max}}$ ) or greater intensity leads to further positive changes inhibition and set-shifting. Only one study examined the effect of chronic AE exercise on attention and working memory, which makes synthesizing a dose-response relationship impossible.

Acute exercise is suggested to facilitate the neurotransmission of catecholamines and brain function, whereas a chronic exercise is required to evoke morphological changes (Thomas et al., 2012). No study has examined possible effects of exercise on gray matter in PFC in children; however, evidence has shown that an increased childhood aerobic fitness is associated with more significant dorsal striatal volumes and that this is related to enhanced cognitive control and brain structural change (Chaddock et al., 2010). Since youth with ADHD are characterized by volume reductions in several prefrontal brain regions (Stevens & Haney-Caron, 2012), AE might benefit their delayed structural maturation. Regarding the white matter, evidence supports that exercise increases white matter microstructure in children (Chaddock-Heyman et al., 2018). In 2014, researchers reported that an eight-month AE intervention positively influenced uncinate fasciculus in overweight children (Schaeffer et al., 2014). Similar to ADHD, overweight children are characterized by uncinate perturbation (Yau et al., 2012), which causes impairments in decision-making (Olson et al., 2015; Von Der Heide et al., 2013); however, increased white matter tract integrity might contribute to exercise-induced improvements on EFs in youth with ADHD.

In addition to favorable brain structure changes induced by exercise, there is compelling evidence suggesting positive effects of chronic AE on the brain's functional properties. AEs have been shown to increase the PFC activation (Choi et al., 2015; Moriarty et al., 2019) and to normalize cortical activity in the resting state (Huang et al., 2017). As an insufficient activation of the PFC is related to impairments in goal-oriented behavior, the tendency of AE to facilitate this hypo-aroused state of the central nervous system might partly explain how regular exercise benefits EFs in ADHD.

### ***Strengths and limitations***

The present study represents a novel addition to the literature; indeed, the consideration of how AE dose impacts aspects of EFs has not been investigated in details previously. Moreover, it appears that different doses of AE might differently influence some aspects of EFs; however, this finding rests on preliminary evidence at this stage and thus should be treated with caution.

Despite the strength and novelty of this work, some limitations warrant future consideration. Given our strict inclusion criteria, we did not include studies that were published in languages other than English and we did not include unpublished studies or dissertations, and so may have missed some relevant research. Also, despite the growing research focus on effect of AE on EFs of people with ADHD, only a small number of studies are available and very few studies reported AE dosage, which meant we were limited by a lack of data for inclusion. This study also mostly focused on AE dosage and prescription and did not intend to study other factors (such as family factors) which might directly and indirectly impact EFs.

## Conclusion

The current study shed light on the AE parameters that influence EFs in youth with ADHD. Regarding the acute effects of AE, studies have consistently found improvements in EFs, which were most pronounced in inhibition, set-shifting, and attention aspect of EFs. Such cognitive improvements were reported after children with ADHD engaged in acute AE with 20–30 minutes duration and at least with moderate intensity ( $65\% \leq 80\% \text{HR}_{\text{max}}$ ). It is unclear whether children with ADHD can expect similar or even larger benefits from more intense AE.

Though regular exercise is thought to elicit long-term benefits for cognitive performance in youth with ADHD, a few studies have examined the chronic effects of AE on EFs in children with ADHD, thus hindering evidence-based prescriptions. This study found that at least 45 minutes, with a frequency of 3 days/week for 6–12 weeks and with at least moderate (i.e.,  $60\% \leq 75\% \text{HR}_{\text{max}}$ ) intensity leads to further positive changes in the inhibition and set-shifting.

This study provided information on the dosage of various AE types, the results of this study can benefit practitioners and clinicians in developing more effective interventions for enhancing EFs in children with ADHD. The disparities between acute and chronic AE doses were also analyzed, and suggestions for prescribing AE for children with ADHD were presented, taking into account the type, frequency, and intensity of AE. This review also intended to help in decision-making about AE integration in educational institutions, as well. This study shown that a particular dose of AE as a non-pharmacological treatment might be an excellent alternative for ADHD medication from a clinical standpoint. A number of AE treatments have been shown to be useful in alleviating and even eliminating symptom patterns, and in some circumstances, even substituting standard pharmaceutical therapy. It is a low-cost, noninvasive, non-pharmacological, and always available intervention with preventative qualities. In essence, ADHD deprives people of some of their ability to function, and in some cases, this deprivation is permanent. Exercise routines help these people reach a new level of development by increasing their resilience, cognitive capability, and emotional control. Moreover, Exercise has both biological and psychological benefits on the brain and cognitive performance, as well as promoting a sense of well-being. Exercise contributes in the prevention of both normal and pathological aging. Recent data suggests that exercise causes powerful neuroplastic changes, which are mediated in part by epigenetic processes (Mandolesi et al., 2018). Additionally, an active lifestyle during childhood and adolescence is an important factor in preventing diseases in adulthood (Lefevre et al., 2000; Twisk et al., 2002) which might be important for youth with ADHD if they tend to be less active.

## Future works

Although the findings of this systematic review are encouraging, due to the small number of papers included in the review and the lack of variety in AE dose, this work was unable to establish optimal AE dosage. Nonetheless, it indicates that moderate to vigorous intensity exercise at durations and frequencies, less than the recommended targets of PA for Children (i.e., 60 minutes per day) has beneficial effects on EFs in children with

ADHA. These limited results emphasize the need for additional research in this field to determine optimal dosage. Future studies should study various AE doses on the EFs of youth with ADHD to determine the optimal dose of AE parameters.

### Trial registration

Our study protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO); registration number: CRD42020215404.

### Disclosure statement

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