Mental Health and Physical Activity 27 (2024) 100624

Contents lists available at ScienceDirect

Mental Health and Physical Activity

journal homepage: www.elsevier.com/locate/menpa

Effect of an acute bout of exercise on executive function and sleep in children with attention deficit hyperactivity disorder and autism spectrum disorder

Grace W. Walters [a], Shelley Taylor [a,b], Emma L. Sweeney [a], Simon B. Cooper [a], Ryan A. Williams [a], Karah J. Dring [a,*]

[a] *Sport Health and Performance Enhancement (SHAPE) Research Group, Department of Sport Science, UK*
[b] *Diabetes Research Centre, University of Leicester, Leicester General Hospital, UK*

A R T I C L E I N F O

Keywords:
Neurodiversity
Children
Exercise
Cognitive function
Sleep

A B S T R A C T

Background and aims: The present study aimed to examine the effect of an acute bout of circuit-base exercise on executive function, visual perception and sleep parameters in neurodiverse children.
Methods: After familiarisation, 34 children (4 female) with ADHD and/or ASD completed two trials (30-min circuit-based exercise (E) or a rested control (C) trial) in a randomised, counterbalanced, crossover design. Participants completed cognitive function tests (Stroop test, Sternberg Paradigm and Visual Search Test) at baseline, immediately post-exercise, and the morning after exercise. Participants were provided with a wrist actigraph to wear overnight to determine sleep duration, wake after sleep onset, sleep efficiency, and sleep latency. Statistical analyses were conducted via ANCOVA, with diagnosis included as a covariate.
Results: Accuracy on the Stroop test (complex level) was better maintained following circuit-based exercise when compared with rest immediately post-exercise (E: 1.88% decreased accuracy; C: 4.73% decreased accuracy, $p = 0.009$), and on day two (E: 1.22% increased accuracy; C: 6.37% decreased accuracy; $p < 0.001$). Accuracy on the Sternberg Paradigm (5-item level) was improved immediately post-exercise on the exercise trial when compared with rest (E: 0.37% decreased accuracy; C: 7.29% decreased accuracy; $p = 0.011$). Improvements in accuracy across both tests were at the expense of response time, which was slower on the exercise trial (all $p < 0.05$). Sleep parameters did not differ across trials (all $p > 0.05$).
Conclusion: Moderate intensity circuit-based exercise is an ecologically valid exercise modality that, acutely, improves executive function (compared to rest), which may alleviate the impaired executive function in children with ADHD and ASD.

1. Introduction

Neurodevelopmental conditions, including attention deficit disorder (ADHD) and autism spectrum disorders (ASD) are the most common diagnoses of childhood disability, with ADHD affecting ~8–10% of children (Polanczyk et al., 2014; Salari et al., 2023) and ASD affecting ~0.6% of children globally (Salari et al., 2022). Furthermore, in approximately 21% of cases, young people diagnosed with ADHD go on to have an ASD diagnosis, referred to as co-occurring ADHD and ASD (Young et al., 2020). A common symptom of both ADHD and ASD is an impairment in executive function, a term used to refer to higher level cognitive processes (Diamond, 2014). The three components of executive function are inhibitory control, working memory, and cognitive flexibility (Diamond, 2014); with young people with ADHD and ASD often experiencing deficits across aspects of these three components (Coghill et al., 2018; Daley & Birchwood, 2010); meaning that children with ADHD and ASD may present with an inability to modulate complex behaviours and direct behaviour towards the attainment of a goal, particularly in a classroom setting (Friedman et al., 2015), contributing to poorer academic performance. Children with ADHD also present with impaired visual search performance, when compared with their typically developing peers (Mullane & Klein, 2008), which is potentially due

* Corresponding author. Department of Sport Science, School of Science and Technology, Nottingham Trent University, Clifton campus; Nottingham NG11 8NS, UK.

E-mail address: Karah.Dring@ntu.ac.uk (K.J. Dring).

https://doi.org/10.1016/j.mhpa.2024.100624
Received 9 January 2024; Received in revised form 31 July 2024; Accepted 2 August 2024
Available online 3 August 2024

to the impairments in executive function that they experience. Thus, children with ADHD contend with an inability to select relevant elements in a visual scene, which is a prerequisite for conscious visual perception (Das et al., 2007). Furthermore, impairments in executive function are associated with poor sleep (Holingue et al., 2021; Tsai et al., 2021), which affects ~50–80% of children with ADHD and ASD (Bauman, 2010; Hvolby, 2015). Thus, interventions that provide avenues to acutely enhance executive function and sleep in children with ADHD and ASD are needed.

In children with ADHD, several studies have shown that acute bouts of aerobic exercise (of moderate intensity and 20–45min in duration) improve inhibitory control and cognitive flexibility immediately and up to ~60-min post-exercise; whilst the effect on working memory remains unknown (Chang et al., 2012; Ludyga et al., 2017; Piepmeier et al., 2015; Pontifex et al., 2013; Yu et al., 2020). Furthermore, a recent meta-analysis concluded that, overall, physical activity has a small acute benefit on subsequent cognition in young people with ADHD (Sibbick et al., 2022). However, these effects were domain specific (with positive effects reported for inhibitory control and cognitive flexibility, but not working memory), and depended on characteristics of the physical activity, such as the duration and modality (Sibbick et al., 2022). With regards modality, physical activity that involves an element of cognitive engagement (e.g., games-based activities) was found to yield the largest effect on subsequent cognition (Sibbick et al., 2022). This is an important consideration given that cognitively engaging activity is an attractive modality of physical activity for young people that promotes enjoyment; a key consideration for adherence to physical activity in this population (Srinivasan et al., 2014).

In contrast to the evidence-base regarding acute physical activity and cognition in young people with ADHD, there is a paucity of research examining the effect of acute bouts of exercise on executive function in children with ASD. Previously, an acute bout of moderate intensity, aerobic exercise (cycling) has been reported to impair facial recognition in children with ASD (Ludyga et al., 2023). Thus, research examining the acute effects of physical activity on executive function in young people with ASD (and the most appropriate exercise modality to elicit improvements) remain poorly understood and warrant further examination to provide safe, effective non-pharmacological therapeutic interventions to manage acute symptoms of ASD, such as impairments in executive function.

Young people with neurodevelopmental conditions typically experience poor sleep, including worse sleep onset latency and number of night awakenings (Bauman, 2010; Hvolby, 2015). In neurotypical populations, a small-moderate beneficial effect of exercise on sleep onset latency and sleep quality has been observed (Kredlow et al., 2015). However, it is unknown whether the beneficial effects of exercise on sleep translate to children with neurodevelopmental conditions. Preliminary evidence suggests that an aerobic exercise intervention (45-min jogging each week for 12 weeks) improves sleep efficiency and sleep onset latency in children with ADHD (Liu et al., 2023). There is also evidence that aerobic exercises including aquatics (Ansari et al., 2021; Oriel et al., 2016), jogging (Tse et al., 2022) and cycling (Brand et al., 2015) improve an array of sleep indices in children with ASD. Whilst these early findings promote chronic aerobic exercise programmes for the improvement of sleep parameters in children with neurodiverse conditions, the acute effects of exercise on sleep in children with ADHD and/or ASD are not well understood despite their importance for short-term management of sleep.

Therefore, the main aim of the present study is to determine whether an acute bout of cognitively engaging exercise enhances executive function (including inhibitory control and working memory) and visual perception in children with ADHD and/or ASD. A secondary aim of the study is to determine whether the cognitively engaging exercise circuit improves sleep (measured via sleep actigraphy and parental questionnaires) in children with ADHD and/or ASD.

2. Methods

2.1. Participant characteristics

In total, 40 children (aged 9.9 ± 1.0 y) were recruited to the study. Three participants withdrew and a further three participants did not attend both days of each trial and therefore their data were not included in analyses. A repeated measures power calculation was performed (G*Power 3.1.9.2) based on an effect size of 0.2 (Sibbick et al., 2022), $\alpha = 0.05$ and power = 0.80, the calculation indicated a required sample size of 34. Overall, 34 participants attended both days of each trial (30 male, 4 female). For details of diagnoses, medication status and trial order, please see Table 1.

During familiarisation, body mass (Seca 770 digital scale, Hamburg, Germany) and stature (Leicester Height Measure, Seca, Hamburg, Germany) were measured to determine body mass index (calculated as body mass (kg)/stature (m)^2). Participant characteristics were as follows; stature: 143.9 ± 7.5 cm, body mass: 40.0 ± 8.9 kg, body mass index: 19.2 ± 3.2 kg m^2.

2.2. Study design

The Nottingham Trent University Human Invasive Ethical Advisory Committee provided ethical clearance for this study (approval no. SST-717). Participants were recruited from local special education needs schools and primary schools, following consent from the head teacher. Written informed parental/guardian consent and child assent were also obtained. The following inclusion criteria were applied: (a) professional confirmation the child was living with ADHD, ASD, or co-occurring ADHD/ASD; or an ongoing assessment for the diagnosis of ADHD, ASD, or co-occurring ADHD/ASD; (b) no health conditions affecting participation in the exercise component of the study (e.g., heart conditions); (c) no health conditions affecting completion of the study measures (e.g., heart conditions). The latter two criteria were confirmed by parents/guardians who completed a health screen questionnaire on behalf of the participant.

Familiarisation was completed 7-d prior to the first main experimental trial and provided participants with an overview of the study design and procedures. Following anthropometric measures, participants were familiarised with the battery of cognitive function tests (Stroop test, Sternberg Paradigm, and Visual Search test), and the circuit-based exercise. At the end of the session participants were provided with a wrist actigraph (GENEActiv, Activinsights Ltd., UK) and instructed to wear this to bed for five consecutive nights. Parents/guardians completed a sleep diary for the five nights the wrist actigraph was worn.

2.3. Main experimental trials

Following familiarisation, participants completed two main experimental trials (circuit-based exercise trial and a rested control trial) in a

Table 1
Key participant characteristics.

		Overall (n)	Exercise Trial First (n)	Resting Trial First (n)
Diagnosis	ADHD	11	6	5
	ASD	10	6	4
	ADHD and ASD	13	7	6
Medication Status	No medication	20	9	11
	ADHD monotherapy	5	3	2
	Sleep aid monotherapy	2	1	1
	Dual ADHD and sleep aid therapy	7	4	3

randomised, order-balanced, within-subjects crossover design, which were separated by 7-d. Participants were tested in small groups (of 3–8 participants), with block randomisation (and order-balancing) taking place at the group level due to logistical challenges (ensuring that diagnosis of ADHD, ASD or both was also balanced by trial order). Participants were blinded to the trial condition until they arrived at school. For 24-h prior to and the evening of the first main experimental trial, participants recorded their diet so that this could be repeated during the second main experimental trial. Participants were asked to refrain from any physical activity for 24-h prior to, and throughout, the main experimental trials.

Main experimental trials took place across two days, commencing at ~1.30pm on day one and at ~8.30am on day two (total testing time 4 h for each main trial across two days). The timing of all testing was matched across trials for each participant; with the within-subjects design allowing for the residual effects of the exercise to be established in comparison to the rested control trial (without the interference of any confounding variables such as medication, as this was controlled between trials). On day one, participants arrived and were fitted with a heart rate monitor (Firstbeat Team Sport System, Firstbeat Technologies Ltd, Finland) and completed baseline cognitive function tests (Stroop test, Sternberg Paradigm, and Visual Search test). Participants then completed either the 30-min cognitively engaging exercise circuit (exercise trial) or 30-min of quiet seated rest (rested control trial). Immediately post-exercise or rest participants repeated the cognitive function tests and AD-ACL. Prior to leaving the session, participants were fitted with a wrist actigraph and were given a sleep diary to be completed by their parents/guardians. Following an overnight fast from ~9pm the previous evening, participants reported back to school on day two and consumed a standardised breakfast 30-min prior to a final battery of cognitive tests and AD-ACL questionnaire. Both trials followed a time-matched protocol across both days of the study.

2.4. Experimental measurements

2.4.1. Battery of cognitive function tests

The battery of cognitive function tests included the Stroop test (a measure of information processing and inhibitory control), the Sternberg Paradigm (a measure of visual working memory), and the Visual Search test (a measure of perception), completed in that order. The battery of cognitive function tests were administered on a laptop computer (Lenovo ThinkPad T450, Lenovo, Hong Kong) and lasted ~12-min. Noise cancelling headphones were provided; however due to the prevalence of sensory needs associated with neurodevelopmental conditions participants chose whether or not they felt comfortable wearing these during the tests. To further avoid distractions during the tests, participants sat in a dimly lit room and were seated away from other participants. Prior to each test, verbal instructions were provided by a member of the research team, followed by written instructions on screen for the participant to read. Participants were informed that they should respond to each stimulus correctly and as quickly as possible.

The Stroop test consisted of a simple and complex level and involved the presentation of a test word in the centre of the screen, with a target and distractor presented on the left and right side of the test word. Participants used the arrow keys to select their response. On the simple level, the test word, target word and distractor word were all presented in the same font colour and a total of 20 stimuli were presented. On the complex level, 40 stimuli were presented, with the participant selecting the font colour rather than the word itself. Choices remained on the screen until the participant responded, with an inter-stimulus interval of 1 s. The Stroop test assessed executive function, more specifically the subset of inhibitory control (Miyake et al., 2000); which is of importance given that executive function is a key determinant of academic success (Best et al., 2011).

The Sternberg Paradigm consisted of three levels progressively utilising a different working memory load (one-, three-, or five-item). The one item level consisted of 16 test stimuli and the number '3' was the target. On the three and five item levels (consisting of 32 test stimuli), the target is three or five randomly generated letters, respectively. Each level commenced with the target items along with instructions to press the right arrow key if a target item appeared and the left arrow key if a distractor appeared. The correct response was counterbalanced between the left and right arrow keys for each level. Choice stimuli were presented in the centre of the screen, with an inter-stimulus interval of 1 s. The Sternberg paradigm assessed working memory (Sternberg, 1969), which is also important for academic performance (Rogers et al., 2011).

The visual search test comprised of a simple and complex level. On both levels participants were instructed to press the space key once they detected a triangle on the screen. Following each response, a new target would appear following a random delay (minimum 500 ms). The simple level (consisting of 20 targets) assessed simple visuomotor speed, with triangles drawn in solid green lines on a black background. For the complex level (40 targets) the additional complex visual processing component of a background distractor was introduced, induced by random moving dots on the screen (new distractor dots were re-drawn every 250 ms). Target triangles were initially drawn with just a few visible dots of each line, with the density of these points increased linearly with time until the participants responded. The visual search test assessed perception, providing a holistic approach to the assessment of cognition in the present study.

For all cognitive tests the variables of interest were the response times of correct responses (in ms) and the proportion of correct responses made. Full details relating to each of the cognitive function tests included in the battery are provided in more detail elsewhere (e.g., Gilbert et al., 2023; Williams et al., 2020).

2.4.2. Exercise protocol

During the exercise trial, participants completed a 30-min cognitively engaging exercise circuit indoors in a school sports hall. An experienced member of the research team led the exercise circuit. The circuit consisted of a 5-min warm-up, 20-min of circuit exercises, and a 5-min cool-down. The warm-up included moderate physical activity such as brisk walking and star jumps followed by static and dynamic stretches. The exercise circuit consisted of five exercise stations, each undertaken for 4-min (Table 2); totalling 20-min in duration. The exercise circuit was designed specifically to be cognitively engaging and included updating and inhibiting movement games and bilateral coordinative exercises (based on the work of Budde et al., 2008), to exercise the executive function of the participants as they undertook the physical activity (Table 2). Following this, a 5-min cool down was performed consisting of jogging and walking, followed by static stretches.

2.4.3. Sleep measurements

Sleep was measured via wrist-worn actigraphy devices (GENEActiv, Activinsights Ltd., UK), worn on the non-dominant wrist. Sleep measurements were performed for five consecutive nights following familiarisation to measure habitual sleep, and for one night in each experimental trial. The actigraphy devices were configured with a frequency of 25 Hz. Data were downloaded using GENEActiv software (Activinsights Ltd., UK). Parent/guardian completed sleep diaries were used in conjunction with actigraphy to determine bed and wake time. Wrist actigraphy has high levels of agreement (>90%) with polysomnography (the gold standard measure of sleep duration) (Ancoli-Israel et al., 2003).

Sleep duration, time awake after sleep onset, sleep efficiency, and sleep latency were determined using the GGIR package v2.10–1 (Migueles et al., 2019; van Hees et al., 2015) in RStudio (www.r-project.org). Any nights with no-wear time were excluded from analyses.

2.4.4. Standardised breakfast

On day two of both main experimental trials, a standardised breakfast was provided for participants given the well-documented effects of

Table 2
Detailed description of the circuit-based exercise protocol.

Exercise Type	Description	Time
Bilateral coordinative exercise	Participants were instructed to walk around a coned area bouncing the basketball firstly with their left hand only, then their right hand only, and then using alternative hands.	4-min
Updating and inhibiting movements game (word-movement association game)	The first word-movement association game involved children moving around when they heard the command 'green light' and stop when they heard the 'red light' command. A command was given every 15-s, halfway through this game the commands were reversed, i.e., 'red light' means go, 'green light' means stop.	4-min
Bilateral coordinative exercise	Participants stood, in pairs, either side of a square marked on the floor and were instructed to bounce a tennis ball within the square for their partner to catch. To begin, participants could use only their right hand, and then only their left hand. Participants gradually moved further away from the square if the ball was bounced within the square and their partner caught the ball but took a step closer any time they did not achieve this.	4-min
Updating and inhibiting movements game (word-movement association game)	Participants were given two commands initially which were 'trot' which meant they had to walk and 'gallop' which meant they had to run. A command was given every 15-s. Half- way through the game participants were given a third command of 'hurdle' which meant they had to jump. One of the three commands was given every 15-s.	4-min
Bilateral coordinative exercise	Participants were instructed to chest pass a basketball over a marked square on the floor to their partner and gradually move back as their partner caught the basketball. Half-way through participants were instructed to perform a bounce pass into the marked square, as opposed to a chest pass. Any time the ball did not bounce in the square or their partner failed to catch the pass, participants took a step closer to the square.	4-min

breakfast on cognition (Cooper et al., 2011). Breakfast provided 1.5 g kg^{-1} body mass of carbohydrate and included cornflakes, milk, white toast, and butter; identical to that used previously (e.g., Dring et al., 2019). Participants had 15-min to consume the standardised breakfast. Water was allowed *ad libitum* throughout breakfast and the rest of the main experimental trials.

2.5. Statistical analysis

Response time and accuracy analyses for the cognitive function tests were conducted using R (www.r-project.org). Response time analyses were performed using the *nlme* package, which implements mixed effect models and yields *t* statistics. Accuracy analyses were performed using the *lme4* package, which implements mixed effect models for data with a binomial outcome distribution and yields *z* statistics. All analyses were conducted using a three-way (trial * time * test level) interaction, with subsequent two-way (trial*time) interactions performed as necessary to further explore any significant three-way interactions. Prior to analyses, response times were log transformed to exhibit the right-hand skew, typical of human response times. Sleep data were analysed in SPSS (version 29) via two-way (trial by time) repeated measures ANOVA, with diagnosis (ASD, ADHD or co-occurring) included as a covariate. All data are presented as mean ± standard deviation, unless stated otherwise. Statistical significance was accepted as $p < 0.05$.

3. Results

The circuit-based exercise was of moderate intensity, with an average heart rate of 154 ± 16 beats. min^{-1} and a maximum heart rate of 184 ± 17 beats. min^{-1}.

3.1. Cognitive data

3.1.1. Overview

In total, 27 participants completed all three cognitive tests (Stoop test, Sternberg Paradigm, and Visual Search test) at each time point (pre-exercise, immediately post-exercise, and the following morning after the consumption of the standardised breakfast). A total of seven participants have data missing for the cognitive function tests from at least one time point due to temporary non-compliance, hence the reduced n number for this battery of tests. Data for each of the cognitive function tests are displayed in Table 3.

3.1.2. Stroop test

3.1.2.1. Response time. On day one, the pattern of change in response times on the Stroop test between the exercise and resting trials was similar on both the simple and complex levels (trial * time * test level interaction, $p = 0.736$). However, on day 2, the pattern of change in response times between the trials tended to be different across test levels (trial * time * test level interaction, $t_{(10496)} = -1.91$, $p = 0.057$). Upon further inspection, whilst response times improved on day 2 on the resting trial on both test levels, response times also improved on day 2 on the exercise trial but only on the complex level of the Stroop test. Further analyses revealed that, overall, the pattern of change in response times was similar immediately post-exercise between trials (trial * time interaction, $p = 0.395$); but on day 2 the improvement in response times was greater on the resting trial (trial * time interaction, $t_{(10496)} = -3.24$,

Table 3
Cognitive function data across the exercise and rested control trials. Data are mean ± SD.

Test	Test Level	Variable	Exercise			Rest		
			Pre	Immediately Post	Day-2	Pre	Immediately Post	Day-2
Stroop	Simple	Response Time [ms]	1040 ± 361	1147 ± 415	1056 ± 352	1273 ± 429	13701 ± 334	1035 ± 354
		Accuracy [%]	94 ± 10	91 ± 16	94 ± 13	98 ± 4	94 ± 8	92 ± 14
	Complex	Response Time [ms]	1415 ± 425	1381 ± 557	1361 ± 431	1567 ± 391.0	1488 ± 407	1295 ± 433
		Accuracy [%]	90 ± 13	88 ± 17	92 ± 12	94 ± 5	90 ± 13	87 ± 18
Sternberg	1-item	Response Time [ms]	766 ± 189	786 ± 191	800 ± 233	790 ± 163	787 ± 230	764 ± 224
		Accuracy [%]	94 ± 7	94 ± 11	95 ± 6	93 ± 10	91 ± 14	93 ± 8
	3-item	Response Time [ms]	991 ± 227	924 ± 274	950 ± 245	943 ± 167	891 ± 284	973 ± 254
		Accuracy [%]	89 ± 15	84 ± 20	86 ± 17	90 ± 11	82 ± 21	88 ± 15
	5-item	Response Time [ms]	1010 ± 371	1108 ± 481	1130 ± 384	1083 ± 269	998 ± 314	1153 ± 351
		Accuracy [%]	77 ± 19	76 ± 23	79 ± 15	81 ± 18	76 ± 20	82 ± 16
Visual Search	Simple	Response Time [ms]	722 ± 131	746 ± 132	732 ± 118	744 ± 147	763 ± 158	730 ± 127
		Accuracy [%]	76 ± 29	67 ± 32	88 ± 19	79 ± 28	73 ± 32	81 ± 21
	Complex	Response Time [ms]	1691 ± 540	1645 ± 418	1855 ± 613	1620 ± 437	1642 ± 565	1628 ± 542
		Accuracy [%]	76 ± 31	75 ± 30	83 ± 28	73 ± 32	75 ± 28	86 ± 21

$p = 0.001$).

3.1.2.2. Accuracy. The pattern of change in accuracy on the Stroop test between the exercise and resting trials was similar on both the simple and complex levels, both on day one (trial * time * test level interaction, $p = 0.822$) and day two (trial * time * test level interaction, $p = 0.930$). Upon further inspection, accuracy on the Stroop test was better maintained on the exercise trial, compared to the resting trial, both on day one (trial * time interaction, $z_{(12225)} = -2.63$, $p = 0.009$) and day two (trial * time interaction, $z_{(12225)} = -5.10$, $p < 0.001$).

3.1.3. Sternberg Paradigm

3.1.3.1. Response time. On day one, the pattern of change in response times on the Sternberg paradigm between the exercise and resting trials was similar on all levels (trial * time * test level interaction, $p = 0.306$). However, on day 2, the pattern of change in response times between the trials tended to be different the test levels (trial * time * test level interaction, $t_{(9071)} = -2.14$, $p = 0.032$). Upon further inspection, whilst response times improved to a greater extent on day two the resting trial on the one item level, response times were improved on day two of the exercise trial on the more complex levels of the Sternberg paradigm.

3.1.3.2. Accuracy. The pattern of change in accuracy on the Sternberg paradigm between the exercise and resting trials was similar on all test levels, both on day one (trial * time * test level interaction, $p = 0.706$) and day two (trial * time * test level interaction, $p = 0.920$). Upon further inspection, regardless of test level accuracy on the Sternberg paradigm was improved on day one on the exercise trial (trial * time interaction, $z_{(11235)} = -2.61$, $p = 0.009$), but was unaffected on day two (trial * time interaction, $p = 0.959$).

3.1.4. Visual search test

3.1.4.1. Response time. The pattern of change in response times on the visual search test between the exercise and resting trials was similar on both test levels on day one (trial * time * test level interaction, $p = 0.906$). However, on day 2, the pattern of change in response times between the trials tended to be different across the test levels (trial * time * test level interaction, $t_{(7568)} = -1.80$, $p = 0.072$). Upon further inspection, response times were improved on day 2 on the exercise trial on the complex level of the visual search test only, whilst response times were unaffected on the resting trial on both test levels.

3.1.4.2. Accuracy. The pattern of change in accuracy on the visual search test between the exercise and resting trials was similar on both the simple and complex levels on day one (trial * time * test level interaction, $p = 0.137$). However, on day 2, the pattern of change in accuracy between the trials was different the test levels (trial * time * test level interaction, $z_{(16451)} = 7.09$, $p < 0.001$). Upon further inspection, accuracy on the simple level of the visual search test was enhanced on day one on the exercise trial only; whereas on the complex level accuracy was enhanced on day one on the resting trial only, but was enhanced on day two on both the exercise and resting trials. These effects yielded significant two-way trial by time interactions, whereby accuracy was enhanced by a greater extent on the exercise trial (compared to the resting trial) both on day one (trial * time interaction, $z_{(16451)} = -2.37$, $p = 0.018$) and day two (trial * time interaction, $z_{(16451)} = -4.25$, $p < 0.001$).

3.2. Sleep

3.2.1. Sleep actigraphy

Overall, 20 participants provided sufficient sleep data for analysis at baseline (habitual sleep) and the night of day one on each experimental trial. Habitual total sleep time was 8.00 ± 0.66 h, habitual wake after sleep onset was 1.18 ± 0.38 h, habitual sleep efficiency was 78.36 ± 5.21%, and habitual sleep onset latency was 42.21 ± 24.14 min. There was no effect of the exercise or rested control trial on any of the sleep parameters; with no difference between trials in total sleep time ($p = 0.325$), wake after sleep onset ($p = 0.369$), sleep efficiency ($p = 0.112$) or sleep latency ($p = 0.829$).

4. Discussion

The main findings of the present study demonstrate that a 30-min bout of cognitively engaging circuit-based exercise of moderate intensity (average heart rate 154 ± 16 beats. min^{-1}) improved executive function and perception in children with neurodevelopmental disorders. Specifically, following the circuit-based exercise the adolescents with ADHD and/or ASD experienced a speed accuracy trade-off whereby their responses on the Stroop test (a measure of inhibitory control) were more accurate, at the expense of response speed. Furthermore, the cognitively engaging exercise enhanced working memory (as measured by the Sternberg Paradigm) immediately post-exercise, when compared with the rested control trial. Finally, perception (as assessed by the visual search test) was also enhanced following the 30-min cognitively engaging exercise circuit, particularly on day two. A further important finding was that the benefits of the cognitively engaging exercise circuit were more evident on the more complex levels of the cognitive tasks, indicating a specific effect on more complex aspects of cognitive function. Whilst beneficial effects were observed on executive function, the circuit-based exercise did not affect sleep in young people with neurodevelopmental conditions.

The present study is the first, to the authors' knowledge to report that cognitively engaging, circuit-based exercise (designed to be ecologically valid) improves inhibitory control, working memory and perception in children with neurodevelopmental conditions. Previously, aerobic exercises (jogging and cycling) have only improved inhibitory control with no effects on working memory in children with ASD (Ansari et al., 2021; Oriel et al., 2016; Tse et al., 2022). Similarly, in children with ADHD mixed martial arts (the most examined exercise mode) improved inhibitory control yet had no effect on working memory (Chang et al., 2012; Ludyga et al., 2017; Piepmeier et al., 2015; Pontifex et al., 2013; Yu et al., 2020). The main finding of the present study is extremely important for children with ADHD and/or ASD as one of the most cited symptoms of these conditions is deficits in executive function, particularly inhibitory control and working memory (Coghill et al., 2018; Daley & Birchwood, 2010). The present study examined the *acute* effects of circuit-based exercise on executive function in children with neurodevelopmental conditions, which are important for the management of common symptoms (impairments in executive function and visual perception) of ADHD and ASD when immediate strategy is required (for example, when faced with a challenge such as an exam which often determine academic achievement).

Furthermore, the present study extends existing findings by reporting that the improvements in inhibitory control, working memory and perception persist into the day following exercise. Previously the residual effects of exercise on cognitive function in young people with neurodevelopmental conditions has only been examined immediately, and up to 60-min, post-exercise (Chang et al., 2012; Ludyga et al., 2017; Piepmeier et al., 2015; Pontifex et al., 2013; Yu et al., 2020). Through examining the residual effects of exercise on executive function into the day after exercise, the findings of the present study extend knowledge and are a starting point for the determination of the optimum frequency of exercise in this population; this is important for the development of strategies to manage common symptoms of ADHD and ASD during challenging situations, such as exams. The findings of this study suggest that the beneficial effects of an afternoon bout of exercise in this population are still evident the following morning.

A novel finding of the present study was that, when considering task complexity (test level during the assessment of cognitive function) the beneficial effects of the exercise circuit were of greater magnitude during the complex levels of each cognitive function test (Stroop test, Sternberg Paradigm and Visual Search test) than during the simple levels. Little research has been undertaken to date examining the effect of exercise on cognitive function task complexity, thus meaning this is a novel finding of the present study. Further investigation is necessary to understand the mechanisms through which cognitive performance improves more during complex cognitive tasks than during simple tasks in children with ADHD and ASD following exercise. Regardless, the findings are of interest and emphasise the potential for cognitively engaging exercise to acutely enhance more complex cognitive tasks, especially as such complex cognitive processes are detrimentally affected in young people with ADHD and/or ASD.

In the present study, there was no effect of the cognitively engaging, circuit-based exercise on sleep later that evening. We examined sleep in this study because a common symptom of ADHD and ASD is disturbed sleep (Bauman, 2010; Hvolby, 2015). In neurotypical populations, an acute bout of exercise has been observed to improve sleep parameters including reduced sleep onset latency and improved sleep quality (Kredlow et al., 2015). However, these beneficial effects were not evident in the present study. Whilst the present study did not find an effect of an acute bout of exercise on sleep, it might be that for circuit-based exercise to improve sleep participation needs to be longer term; as has been reported in previous research examining aerobic exercise training (Ansari et al., 2021; Oriel et al., 2016; Tse et al., 2022). Therefore, the chronic effects of ecologically valid and enjoyable circuit-based exercise on sleep in young people with neurodevelopmental conditions warrant further research.

Finally, the cognitively engaging, circuit-based exercise was designed with the consideration of the symptoms and needs of children with ADHD and/or ASD; and such that it could feasibly be implemented within a school day. Previous research has typically examined the effect of aerobic exercise on cognitive function in children with ASD (Ansari et al., 2021; Oriel et al., 2016; Tse et al., 2022). Aerobic exercises have limited ecological validity in all children given it is repetitive in nature and lacks the key element of being fun. The circuit-based exercise session examined in the present study was designed to use equipment that would be readily available in a school setting, does not require specialist training to be delivered, and offers variety in the activities undertaken, which is important for children with ADHD and/or ASD (Srinivasan et al., 2014). The exercise circuit was also designed to be 30-min in duration, which aligns with the Government requirement that schools provide 30-min of in-school physical activity each day. Therefore, a key strength of the present study is that the exercise modality is ecologically valid and concurrently enhanced executive function.

However, the present study is not without limitation. For example, a reduced number of participants completed the sleep actigraphy measures (20 of 34), and some participants did not complete all cognitive tests at all time points (full data were available from 27 of 34 participants). This is a challenge when working with young people with neurodevelopmental conditions (due to their needs associated with the conditions) and should be considered when designing future research in this area. Some possible strategies to mitigate these issues could include limiting the number of measures taken and working closely in conjunction with schools and parents to enhance adherence (as in the present study). Future work could also consider adding an active control condition, whilst being mindful of overburdening participants in these studies. Furthermore, this study considered the effects of the cognitively engaging exercise circuit on executive function and sleep concurrently; future work could also examine the mechanistic role of effects on sleep for subsequent executive function. In addition, due to the confines of working with children with ADHD and ASD within the field, there were elements of control within the study that should be discussed as a limitation, including the choice to request participants completed a food diary (for replication of subsequent trials), rather than providing a standardised lunch on day one of the study; such a limitation exists as the food consumed prior to cognitive function tests can affect performance (Cohen et al., 2016), and thus having limited control in this regard, acts as a limitation that should be considered when interpreting our main findings. Finally, the present study specifically examined children with ADHD and ASD, and predominantly boys (given the higher prevalence of these conditions in boys); further research is required to confirm the extent to which these findings apply to young people with other neurodevelopmental disorders, and girls with neurodevelopmental disorders.

In conclusion, a 30-min bout of moderate intensity circuit-based exercise improves executive function (inhibitory control and working memory) immediately and the morning after the exercise was completed. However, the exercise circuit had no effect on sleep parameters the evening following the completion of the exercise circuit. The findings of the present study are important as children with neurodevelopmental conditions often experience detriments in their executive function and to have an ecologically valid mode of exercise that acutely enhances executive function is important for developing strategies through which common symptoms of ADHD and/or ASD can be managed.

Funding

This work was supported by The Waterloo Foundation [grant number 610/4690].

Role of the funding source

The Waterloo Foundation had no influence in the study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

CRediT authorship contribution statement

Grace W. Walters: Writing – original draft, Project administration, Investigation, Formal analysis. **Shelley Taylor:** Resources, Project administration, Methodology, Investigation. **Emma L. Sweeney:** Writing – review & editing, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Simon B. Cooper:** Writing – review & editing, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ryan A. Williams:** Project administration, Methodology, Investigation. **Karah J. Dring:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

The research presented in the present study was funded by The Waterloo Foundation. However, The Waterloo Foundation have had no influence over the study design, analysis, writing of the study, or where the authors have chosen to submit the research for publication.

Data availability

Data will be made available on request.

References

Ancoli-Israel, S., Cole, R., Alessi, C., Chambers, M., Moorcroft, W., & Pollak, C. P. (2003). The role of actigraphy in the study of sleep and circadian rhythms. *Sleep, 26*(3), 342–392.

Ansari, S., AdibSaber, F., Elmieh, A., & Gholamrezaei, S. (2021). The effect of water-based intervention on sleep habits and two sleep-related cytokines in children with autism. *Sleep Medicine, 82*, 78–83.

Bauman, M. L. (2010). Medical comorbidities in autism: Challenges to diagnosis and treatment. *The Journal of the American Society for Experimental Neurotherapeutics, 7*, 320–327.

Best, J. R., Miller, P. H., & Naglieri, J. A. (2011). Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample. *Learning and Individual Differences, 21*(4), 327–336.

Brand, S., Jossen, S., Holsboer-Trachsler, E., Pühse, U., & Gerber, M. (2015). Impact of aerobic exercise on sleep and motor skills in children with autism spectrum disorders–a pilot study. *Neuropsychiatric Disease and Treatment, 11*, 1911.

Budde, H., Voelcker-Rehage, C., Pietraßyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters, 441*(2), 219–223.

Chang, Y. K., Liu, S., Yu, H. H., & Lee, Y. H. (2012). Effect of acute exercise on executive function in children with attention deficit hyperactivity disorder. *Archives of Clinical Neuropsychology, 27*(2), 225–237.

Coghill, D., Toplak, M., Rhodes, S., & Adamo, N. (2018). *Cognitive functioning in ADHD*. United Kingdom: Oxford.

Cohen, J. F., Gorski, M. T., Gruber, S. A., Kurdziel, L. B. F., & Rimm, E. B. (2016). The effect of healthy dietary consumption on executive cognitive functioning in children and adolescents: A systematic review. *British Journal of Nutrition, 116*(6), 989–1000.

Cooper, S. B., Bandelow, S., & Nevill, M. E. (2011). Breakfast consumption and cognitive function in adolescent schoolchildren. *Physiology & Behavior, 103*, 431–439.

Daley, D., & Birchwood, J. (2010). ADHD and academic performance: Why does ADHD impact on academic performance and what can be done to support ADHD children in the classroom. *Child: Care, Health and Development, 36*(4), 455–464.

Das, M., Bennett, D. M., & Dutton, G. N. (2007). Visual attention as an important visual function: An outline of manifestations, diagnosis and management of impaired visual attention. *British Journal of Ophthalmology, 91*(11), 1556–1560. https://doi.org/10.1136/bjo.2006.104844

Diamond, A. (2014). Want to optimise executive functions and academic outcomes?: Simple, just nourish the human spirit. *Minnesota Symposia on Child Psychology, 37*, 205–232.

Dring, K. J., Cooper, S. B., Morris, J. G., Sunderland, C., Foulds, G. A., Pockley, A. G., & Nevill, M. E. (2019). Cytokine, glycemic, and insulinemic responses to an acute bout of games-based activity in adolescents. *Scandinavian Journal of Medicine & Science in Sports, 29*(4), 597–605.

Friedman, N. D., Politte, L. C., Nowinski, L. A., & McDougle, C. J. (2015). Autism spectrum disorder. *Psychiatry*, 722–747.

Gilbert, L. M., Dring, K. J., Williams, R. A., Boat, R., Sunderland, C., Morris, J. G., Nevill, M. E., & Cooper, S. B. (2023). Effects of a games-based physical education lesson on cognitive function in adolescents. *Frontiers in Psychology, 14*, Article 1098861.

Holingue, C., Volk, H., Crocetti, D., Gottlieb, B., Spira, A. P., & Mostofsky, S. H. (2021). Links between parent-reported measures of poor sleep and executive function in childhood autism and attention deficit hyperactivity disorder. *Sleep Health, 7*(3), 375–383.

Hvolby, A. (2015). Associations of sleep disturbance with ADHD: Implications for treatment. *Attention Deficit Hyperactivity Disorder, 7*, 1–18.

Kredlow, M. A., Capozzoli, M. C., Hearon, B. A., Calkins, A. W., & Otto, M. W. (2015). The effects of physical activity on sleep: A meta-analytic review. *Journal of Behavioral Medicine, 38*, 427–449.

Liu, H. L. V., Sun, F., & Tse, C. Y. A. (2023). Examining the impact of physical activity on sleep quality in children with ADHD. *Journal of Attention Disorders*, Article 10870547231171723.

Ludyga, S., Brand, S., Gerber, M., Weber, P., Brotzmann, M., Habibifar, F., & Pühse, U. (2017). An event-related potential investigation of the acute effects of aerobic and coordinative exercise on inhibitory control in children with ADHD. *Developmental Cognitive Neuroscience, 28*, 21–28.

Ludyga, S., Gerber, M., Bruggisser, F., Leuenberger, R., Brotzmann, M., Trescher, S., … Hanke, M. (2023). A randomized cross-over trial investigating the neurocognitive effects of acute exercise on face recognition in children with autism spectrum disorder. *Autism Research, 16*(8), 1630–1639.

Migueles, J., Rowlands, A., Huber, F., Sabia, S., & van Hees, V. (2019). Ggir: A research community-driven open-source R package for generating physical activity and sleep outcomes from multi-day raw accelerometer data. *Journal for the Measurement of Physical Behavior, 2*(3), 188–196.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100.

Mullane, J. C., & Klein, R. M. (2008). Literature review: Visual search by children with and without ADHD. *Journal of Attention Disorders, 12*(1), 44–53.

Oriel, K. N., Kanupka, J. W., DeLong, K. S., & Noel, K. (2016). The impact of aquatic exercise on sleep behaviors in children with autism spectrum disorder: A pilot study. *Focus on Autism and Other Developmental Disabilities, 31*(4), 254–261.

Piepmeier, A. T., Shih, C. H., Whedon, M., Williams, L. M., Davis, M. E., Henning, D. A., & Etnier, J. L. (2015). The effect of acute exercise on cognitive performance in children with and without ADHD. *Journal of Sport and Health Science, 4*(1), 97–104.

Polanczyk, G. V., Willcutt, E. G., Salum, G. A., Kieling, C., & Rohde, L. A. (2014). ADHD prevalence estimates across three decades: An updated systematic review and meta-regression analysis. *International Journal of Epidemiology, 43*(2), 434–442.

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

Rogers, M., Hwang, H., Toplak, M., Weiss, M., & Tannock, R. (2011). Inattention, working memory, and academic achievement in adolescents referred for attention deficit/hyperactivity disorder (ADHD). *Child Neuropsychology, 17*(5), 444–458.

Salari, N., Ghasemi, H., Abdoli, N., Rahmani, A., Shiri, M. H., Hashemian, A. H., & Mohammadi, M. (2023). The global prevalence of ADHD in children and adolescents: A systematic review and meta-analysis. *Italian Journal of Pediatrics, 49*(1), 48.

Salari, N., Rasoulpoor, S., Rasoulpoor, S., Shohaimi, S., Jafarpour, S., Abdoli, N., & Mohammadi, M. (2022). The global prevalence of autism spectrum disorder: A comprehensive systematic review and meta-analysis. *Italian Journal of Pediatrics, 48*(1), 1–16.

Sibbick, E., Boat, R., Sarkar, M., Groom, M., & Cooper, S. B. (2022). Acute effects of physical activity on cognitive function in children and adolescents with attention-deficit/hyperactivity disorder: A systematic review and meta-analysis. *Mental Health and Physical Activity*, Article 100469.

Srinivasan, S. M., Pescatello, L. S., & Bhat, A. N. (2014). Current perspectives on physical activity and exercise recommendations for children and adolescents with autism spectrum disorders. *Physical Therapy, 94*(6), 875–889.

Sternberg, S. (1969). Memory-scanning: Mental processes revealed by reaction-time experiments. *American Scientist, 57*(4), 421–457.

Tsai, T. H., Chen, Y. L., & Gau, S. S. F. (2021). Relationships between autistic traits, insufficient sleep, and real-world executive functions in children: A mediation analysis of a national epidemiological survey. *Psychological Medicine, 51*(4), 579–586.

Tse, A. C., Lee, P. H., Zhang, J., Chan, R. C., Ho, A. W., & Lai, E. W. (2022). Effects of exercise on sleep, melatonin level, and behavioral functioning in children with autism. *Autism, 26*(7), 1712–1722.

van Hees, V., Sabia, S., Anderson, K., Denton, S., Oliver, J., Catt, M., Abell, J., Kivimaki, M., Trenell, M., & Singh-Manoux, A. (2015). A novel, open access method to assess sleep duration using a wrist-worn accelerometer. *PLoS One, 10*(11), Article e0142533. https://doi.org/10.1371/journal.pone.0142533

Williams, R. A., Cooper, S. B., Dring, K. J., Hatch, L., Morris, J. G., Sunderland, C., & Nevill, M. E. (2020). Effect of football activity and physical fitness on information processing, inhibitory control and working memory in adolescents. *BMC Public Health, 20*, 1–14.

Young, S., Hollingdale, J., Absoud, M., Bolton, P., Branney, P., Colley, W., & Woodhouse, E. (2020). Guidance for identification and treatment of individuals with attention deficit/hyperactivity disorder and autism spectrum disorder based upon expert consensus. *BMC Medicine, 18*(1), 1–29.

Yu, C. L., Hsieh, S. S., Chueh, T. Y., Huang, C. J., Hillman, C. H., & Hung, T. M. (2020). The effects of acute aerobic exercise on inhibitory control and resting state heart rate variability in children with ADHD. *Scientific Reports, 10*(1), Article 19958.