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Outdoor physical activity is more beneficial than indoor physical activity for cognition in young people

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ABSTRACT

Background: Substantial evidence demonstrates the beneficial acute effect of physical activity and the outdoor environment independently on cognitive function. However, evidence for their potential synergistic effects remain unknown.

Methods: Following familiarisation, forty-five children (aged 11–13 years) took part in an identical physical activity session outdoors and indoors; and completed a battery of cognitive tests (Stroop test, Sternberg paradigm, and Flanker task) before, immediately post-, and 45 min post-physical activity.

Results: Following outdoor, compared to indoor, physical activity response time was improved more immediately post-physical activity on the 3-item level of the Sternberg Paradigm (-34 ms *vs* +14 ms; $P = 0.001$), at 45 min post-physical activity on the complex level of the Stroop test (-94 ms *vs* -20 ms; $P = 0.002$), the 1-item (-9 ms *vs* +71 ms; $P = 0.026$) and 3-item level of the Sternberg paradigm (-37 ms *vs* +69 ms; $P < 0.001$), and the congruent level of the Flanker test (-44 ms *vs* -14 ms; $P = 0.001$). Accuracy was also improved more outdoors (compared to indoors) immediately post-physical activity (+2.0 % *vs* +0.4 %; $P = 0.036$) and 45 min post-physical activity (+2.0 % *vs* +0.1 %; $P = 0.043$) on the complex level of the Stroop test and on the incongruent level of the Flanker test (no change *vs* -3 %; $P = 0.008$).

Discussion: This is the first study to demonstrate superior cognitive benefits of outdoor, compared to indoor, physical activity. The overarching finding of this investigation is that physical activity performed outdoors significantly improves cognitive function more than when performed indoors, suggesting a synergistic effect between physical activity and the outdoor environment.

1. Introduction

Cognitive function, defined as a variety of brain-mediated functions and processes [1], allows for the perception, evaluation, storage, manipulation, and use of information from both external (*e.g.*, environment) and internal (*e.g.*, experiences, memory) sources prior to responding to such information [1]. Cognitive function consists of six main domains: psychomotor, memory, attention, perception, language, and executive function [1], which all play a vital role in, and are the foundation of, academic ability [2]. Executive function is a series of higher-order cognitive processes including reasoning, planning, completing goal-directed actions, and more [3]. Executive functions are indispensable for success throughout life [4], they play a crucial role in children's and adolescent's academic performance [5], social–emotional development [6], and mental and physical health [7]. Executive function can be divided into (1) core executive functions (*i.e.*, inhibitory control, working memory and cognitive flexibility); and (2) higher-level executive functions (*e.g.*, reasoning, planning and problem-solving) [8].

The influence of various factors on cognitive function among school aged children have been explored including nutrition (most commonly breakfast consumption) (*e.g.*, Cooper, Bandelow, & Nevill, 2011 [9]; Mahoney et al., 2005 [10]) and physical activity (*e.g.*, Hillman et al., 2009 [11]; Hatch et al., 2021 [12]). Physical activity is of particular interest given that despite the well know multi-faceted health benefits associated with participation in physical activity [13,14], in the most recent academic year (2023/24) <50 % of children and young people in the UK met the Chief Medical Officers' guidelines for physical activity participation [15].

Over the past two decades, a growing number of review studies have summarised the acute effects of physical activity on cognitive function,

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with a recent comprehensive meta-analysis yielding a small-to-medium overall effect size (SMD = 0.33) [16]. Furthermore, a number of reviews have been conducted specifically in children and adolescents (*e.g.*, Donnelly et al., 2016 [17]; Alvarez-Bueno et al., 2016 [8]; De Greeff et al., 2018 [18]; Sun et al., 2021 [19]) with the majority supporting the view that physical activity benefits children's cognitive functioning. Evidence from several systematic reviews and meta-analyses demonstrate a small but beneficial effect of acute bouts of physical activity on cognitive function across a range of domains of cognition, including, cognitive flexibility [20,21]; inhibitory control [20,22]; attention [18, 20,22]; processing speed [22]; and working memory [21].

In addition to the beneficial effects of physical activity, another factor that has been proposed to have favourable effects on cognitive function is the outdoor environment and nature. The outdoor environment has been demonstrated to improve selective attention, sustained attention, and working memory [23]. Such favourable effects have been reported among various groups including university students [24] and primary and secondary school aged children [25–32]. The underlying explanation for the positive cognitive effects is that nature recovers mental resources as it increases attentional capacity [33] which is crucial in executing cognitive tasks [34,35]. Therefore, given that time spent outdoors and physical activity can both independently enhance cognitive function, there is potential for a synergistic effect of the two, meaning that performing physical activity outdoors may have an even larger impact on cognitive function as opposed to either component independently.

However, to date trials comparing the effects of indoor and outdoor physical activity on cognitive function are lacking. Many investigations have explored the effects of outdoor *vs* indoor physical activity on aspects of wellbeing [36], psychological/mental health, and perceived exertion [37]; all reporting a superior effect of the outdoor environment compared to indoors. Additionally, an observational trial examined the amount of outdoor *vs* indoor physical activity that young children partake in, and how this correlates with executive function [38]. The investigators observed and documented the amount of outdoor and indoor free play pre-school children took part in and explored how this related to their attention during classroom time. The results demonstrated that children showed greater attention following outdoor play, however this may be due to a higher percentage of time spent in moderate-to-vigorous physical activity and non-sedentary activities during time spent outdoors [38]. However, this study was observational with no control for type, duration, or intensity of physical activity; all of which can impact cognitive function. It also only involved young children (aged 3–6 years) therefore, the effects in older children and adolescents, where arguably cognition is even more important due to the emphasis placed on academic achievement, are unknown.

Presently there has been only one investigation in adolescents comparing the effects of outdoor and indoor physical activity on cognitive function. In this four-arm cluster randomised controlled trial [39] adolescents (aged 14.3 ± 0.5 years) took part in circuit-based physical activity in either a park (outdoors), in nature (outdoors), or indoors, or were in a non-exercise indoor control group, and completed cognitive testing pre- and post-physical activity (6 min post). The authors reported a greater improvement in sustained attention accuracy following physical activity performed indoors *vs* in a park but there was no difference between conditions (indoor *vs* park *vs* nature) on post-physical activity working memory. However, this investigation examined a relatively narrow age range of adolescents (14–15 years), only explored cognitive function immediately post-physical activity, only explored two domains of cognitive function (sustained attention and working memory), used a relatively short duration of physical activity (21 min), and used circuit-based physical activity, which is not representative of the type of physical activity usually engaged in by adolescents (team sports are the most common form of physical activity engaged in among 11–16 year olds, while engagement in 'gym and fitness' type activities is almost half that of team sports [40]). Therefore, given the limitations of this previous study (the only study to date that has explored a direct comparison in cognitive function outcomes in identical indoor *vs* outdoor physical activity) further research which addresses these limitations is needed.

Therefore, the aim of this investigation was to compare the acute effects of performing an identical games-based physical activity session outdoors and indoors on cognitive function in young people aged 11–13 years. We hypothesised that there would be a superior cognitive benefit of performing physical activity outdoors compared to when performed indoors.

2. Methods

2.1. Participant characteristics

Fifty children (aged 11–13 years) were recruited from two secondary schools in the East Midlands area of the UK (participant characteristics are provided in Table 1). Five participants were absent from school on one of the sessions. Therefore, a total of 45 participants completed both the outdoor and indoor trials and were included in analyses. An *a priori* power calculation performed in G*Power [41] based on an effect size of 0.25 [18,20–22], yielded a required sample size of 44.

2.2. Study design

Ethical approval was received from the Nottingham Trent University Human Invasive Ethical Advisory Committee (application ID 1771650), with all methods undertaken thereafter performed in accordance with the relevant guidelines and regulations for school-based research. Headteacher approval for the study to commence and written informed parental/guardian consent were obtained. Parents/guardians also completed a health screen questionnaire on behalf of their child/ dependent, which was checked by a lead investigator to ensure there were no medical conditions (such as a congenital heart condition, or a blood-line relative that had died during or soon after exercise) that would prevent the participant from completing the study. Participant assent (willingness to participate) was also obtained.

Participants completed three data collection visits; including a familiarisation session, and two main experimental trials (outdoor physical activity, and indoor physical activity), in a counterbalanced crossover design, separated by at least 7-days. One group per school did the indoor activity first and the other group at each school did the outdoor session first (n = 23 indoor first; n = 22 outdoor first). The participants took part in the physical activity session during their usual physical education lesson time.

2.3. Familiarisation

During the familiarisation session, participants were introduced to all the procedures involved in the study and were provided with the

Table 1
Participant characteristics.

	Mean ± SDev
Total n	45
Sex (N/% male)	24 (53)
Age (years)	12.44 ± 0.72
Height (m)	1.56 ± 0.10
Body Mass (kg)	46.46 ± 10.53
Body Mass Index (kg/m^2)	19.17 ± 4.31
Waist Circumference (cm)	68.04 ± 11.80
Hip Circumference (cm)	76.86 ± 10.17
Waist: hip ratio	0.90 ± 0.21
MSFT Total Distance (m)	940 ± 460
MSFT Peak HR (beats·min^{-1})	205 ± 11

MSFT: Multistage Fitness Test.

opportunity to ask any questions they had in relation to the study protocol. Participants were familiarised to the physical activity session (to ensure they understood the core components of the physical activity), the battery of cognitive function tests, which were practised to minimise any potential learning effects, and the physical activity enjoyment scale.

Participants first signed an assent form to confirm that they were happy to take part in the study. Following this, anthropometric measures were obtained including body mass (Seca 770 digital scale, Hamburg, Germany) and stature (Leicester Height Measure, Seca, Hamburg, Germany), which were subsequently used to calculate body mass index (BMI). Body composition was assessed using waist and hip circumference.

Participants then completed a battery of cognitive function tests (Stroop test, Sternberg paradigm, and Flanker task), which were first verbally explained by an investigator and participants had an opportunity to ask any questions for clarification. Each test within the battery commenced with 3–6 practice stimuli, with feedback provided relating to whether the correct answer had been chosen. The practice stimuli allowed re-familiarisation with the test to further remove any potential learning effects during the experimental trials. Participants were then fitted with a combined heart rate and global positioning system (GPS) monitor (Polar Team Pro, Polar Electro Oy, Finland), prior to competing the multi-stage fitness test (as a measure of physical fitness).

2.4. Multi-stage fitness test

The multi-stage fitness test is a maximal exercise test that was used to encourage participants to achieve maximal workload and therefore derive maximal heart rate, for subsequent calculation of relative exercise intensity (% of maximum heart rate). During the multi-stage fitness test participants completed 20-metre progressive shuttle runs to the point of volitional exhaustion. The test commenced at a speed of 8.0 km h^{-1} and then increased by 0.5 km h^{-1} for each subsequent 1 min stage completed. During the test, participants were paced by an experienced member of the research team and verbal encouragement was provided to ensure participants reached the point of volitional exhaustion. Heart rate was measured throughout using Polar Team Pro units mounted on a chest worn strap (Polar Team Pro, Polar Electro Oy, Finland).

2.5. Experimental trials

At familiarisation participants were given a food diary to record their food intake on the day of experimental visit one. Participants were asked to replicate their food intake the day of experimental session 2 to prevent food intake differences influencing cognitive function [9,42]. Upon arrival to a classroom (set up as a temporary laboratory) participants performed the battery of cognitive tests. Following this, participants were fitted with chest worn combined heart rate and GPS units before performing the physical activity session either outdoors or indoors. Participants then completed the cognitive test battery immediately and 45 min after the physical activity session. Participants also completed the physical activity enjoyment scale immediately post-physical activity. Both main experimental trials followed identical protocols, with the exception of whether the physical activity session was performed indoors or outdoors (the session itself, the equipment used, court dimensions, group size etc. were identical indoors and outdoors).

2.6. Experimental procedures and measurements

2.6.1. Battery of cognitive function tests

The battery of cognitive function tests included the Stroop test (measure of information processing and inhibitory control), the Sternberg paradigm (measure of visual working memory), and the Flanker task (measure of attention), which were completed in that order. Full details of each of these cognitive tests and are provided elsewhere [12]. The test battery was completed before, immediately post-, and 45 min post-physical activity, and took ~ 15 min to complete all three tests. All tests were administered via a laptop computer (Surface Laptop Go 3, Microsoft). During the cognitive function tests, participants sat separately from one another, in a dimmed room, and wore noise cancelling headphones to minimise distractions. Verbal instructions of each test were provided by a lead investigator, which were followed by written instructions on screen for participants to read. Participants were reminded at the start of each test to answer correctly and as quickly as possible. Outcome variables for each of the tests was the percentage of correct responses (%) and the response time (ms) of correct responses.

2.6.2. Physical activity session

The physical activity session was a 30 min basketball session. Basketball was chosen as the activity given that it allows for high-intensity intermittent activity, and previous experience/a high level of skill are not pre-requisites for participation in the school setting. Furthermore, basketball is a popular games-based physical activity that can be played identically indoors and outdoors, by boys and girls together, and requires relatively minimal equipment that is available in most schools.

The physical activity session is described in detail in supplementary Table 1. Briefly, the session was a 30 min basketball-type physical activity session. The session consisted of a 5 min warm up (pulse raising activities and dynamic stretches), two 5 min competitive basketball specific drills (a dribbling and shooting drill followed by a tag-style game focused on speed, dribbling, and defending), a 10 min small-sided basketball match, and a 5 min cool-down. All drills were designed to be competitive to encourage high levels of moderate-to-vigorous physical activity, and all drills and the 10 min match were small sided, equally, to engage higher levels of moderate-to-vigorous physical activity. To ensure replication of the physical activity session between trials, the court size/dimensions, the basketball nets, the group size, and the instructor were the same for the indoor and outdoor physical activity sessions.

2.6.3. Heart rate

Heart rate was measured continuously throughout each session using the Polar Team Pro units (Polar Team Pro, Polar Electro Oy, Finland), to provide internal load characteristics including average, minimum, and maximum heart rate (supplementary Table 2). The maximum heart rate achieved during the multi-stage fitness test was used to calculate the average and maximum relative exercise intensity of each session (% of maximum heart rate). The units were attached to a chest strap which was fitted to sit on the participants skin at the bottom of their sternum, with the unit positioned in the centre of the chest. The heart rate units were connected via Bluetooth to an iPad (Apple Inc, California, United States). Data were synced to the Polar Team Pro app (Polar Team Pro, Polar Electro Oy, Finland) and then exported to the Polar Team Pro web service (Polar Team Pro, Polar Electro Oy, Finland).

2.6.4. Absolute activity characteristics

The Polar Team Pro units (Polar Team Pro, Polar Electro Oy, Finland) also recorded absolute activity characteristics; including total distance and number of sprints (when set to both indoor and outdoor mode) (supplementary Table 2). This allowed comparison of activity characteristics between the outdoor and indoor trials.

2.6.5. Perceived enjoyment of basketball sessions

The enjoyment of the physical activity sessions was assessed using a revised version of the Physical Activity Enjoyment Scale (PACES), which has been adapted and validated for adolescents [43]. Briefly, the scale consists of 16 statements which originally begin with "When I am physically active…," which were adapted to "When I am taking part in the basketball training session…," followed by the statement (*e.g.*, "I enjoy it"). Items were rated on a 5-point Likert scale (1 = "disagree a lot" to 5 = "agree a lot"). Total activity enjoyment was calculated by summing the 16 responses (seven of which were reverse scored), resulting in a possible range of 16–80, with higher scores reflecting higher enjoyment. The PACES was completed after both the outdoor and indoor training sessions, within 15 min of finishing the exercise (after the immediately post-physical activity cognitive function test battery).

2.7. Statistical analyses

All cognitive data were analysed in the open-source software R (www.r-project.org). Minimum (< 100 ms) and maximum (1000–4000 ms, depending on task complexity) response time cut-offs were applied to eliminate any unreasonably fast (anticipatory) or slow (distracted) responses (as per Hatch et al., 2021 [12] & Cooper et al., 2018 [44]). Cognitive data were then analysed using mixed effect models, using two-way (condition [indoor, outdoor] * time [pre-, immediately post-, 45 min post-physical activity]) repeated measures approach. Response time analyses were conducted using the *nlme* package, which 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 other outcome data (internal load, external load, and PACES score) were compared between the groups using paired samples *t*-tests (IBM SPSS Statistics for Windows, Version 28.0. Armonk, NY: IBM Corp). For all variables, data are presented as mean and standard deviation. Statistical significance was accepted as $p < 0.05$.

3. Results

3.1. Cognitive function

Data for the cognitive tests, at each time point, can be found in Table 2. There were no baseline differences between the trials in any of the cognitive tests (all $P > 0.05$); therefore, figures are displayed as change from baseline for ease of interpretation.

3.1.1. Stroop test- response times

Simple Level: On the simple level of the Stroop test, response time slowed immediately following physical activity on both trials, but to a

Table 2
Cognitive outcomes at each timepoint for each trial.

STROOP TEST	INDOORS *SIMPLE*	INDOORS *COMPLEX*	OUTDOORS *SIMPLE*	OUTDOORS *COMPLEX*
RESPONSE TIME (ms)				
Pre	895 ± 269	1222 ± 293	857 ± 225	1257 ± 294
Immediately-post	903 ± 247	1237 ± 300	917 ± 237	1290 ± 329
Change	8 (-78, 94)	15 (-52, 82)	59 (12, 106)	32 (-28, 93)
45 min-post	951 ± 298	1202 ± 379	900 ± 280	1163 ± 274
Change	57 (-30, 143)	-20 (-119, 80)	43 (-40, 125)	-94 (-160, -28)
ACCURACY (%)				
Pre	98 ± 3	93 ± 7	98 ± 4	92 ± 13
Immediately-post	91 ± 4	94 ± 6	97 ± 4	94 ± 4
Change	-7 (-13, -0.7)	0.4 (-1, 2)	-1 (-2, 1)	2 (-1, 6)
45 min-post	97 ± 4	94 ± 7	97 ± 3	94 ± 5
Change	-2 (-3, -0.2)	0.1 (-3, 3)	-1 (-2, 1)	2 (-1, 6)

STERNBERG PARADIGM	INDOORS *1-ITEM*	INDOORS *3-ITEM*	INDOORS *5-ITEM*	OUTDOORS 1-ITEM	OUTDOORS *3-ITEM*	OUTDOORS *5-ITEM*
RESPONSE TIME (ms)						
Pre	578 ± 129	703 ± 148	911 ± 219	595 ± 189	761 ± 197	911 ± 196
Immediately-post	549 ± 125	717 ± 151	859 ± 214	596 ± 179	727 ± 217	878 ± 195
Change	-29 (-67, 10)	14 (-23, 51)	-53 (113, 7)	1 (-55, 56)	-34 (-110, 42)	-33 (-101, 35)
45 min-post	649 ± 230	771 ± 239	873 ± 224	586 ± 174	724 ± 191	855 ± 212
Change	71 (4, 137)	69 (-3, 140)	-38 (-103, 26)	-9 (-69, 52)	-37 (-82, 8)	56 (-122, 11)
ACCURACY (%)						
Pre	96 ± 5	95 ± 11	88 ± 14	96 ± 6	96 ± 5	90 ± 9
Immediately-post	94 ± 16	92 ± 7	88 ± 12	96 ± 7	94 ± 6	88 ± 11
Change	-2 (-3, 2)	-2.5 (-6, 1)	-1 (-5, 3)	-1 (-3, 2)	-3 (-5, -1)	-2 (-5, 0)
45 min-post	96 ± 5	94 ± 6	87 ± 11	94 ± 7	94 ± 6	87 ± 12
Change	0 (-3, 1)	-1 (-4, 3)	-2 (-5, 2)	-2 (-5, 1)	-2 (-4, 0)	-3 (-6, -1)

FLANKER TEST	INDOORS *CONGRUENT*	INDOORS *INCONGRUENT*	OUTDOORS *CONGRUENT*	OUTDOORS *INCONGRUENT*
RESPONSE TIME (ms)				
Pre	643 ± 148	696 ± 158	660 ± 155	701 ± 160
Immediately-post	636 ± 142	670 ± 157	638 ± 126	690 ± 139
Change	-6 (-36, 23)	-26 (-61, 9)	-22 (-60, 16)	-11 (-52, 30)
45 min-post	628 ± 136	657 ± 135	616 ± 115	645 ± 110
Change	-14 (-47, 18)	-39 (-70, -8)	-44 (-75, 12)	-56 (-90, -22)
ACCURACY (%)				
Pre	98 ± 2	96 ± 5	98 ± 3	95 ± 5
Immediately-post	98 ± 3	95 ± 5	98 ± 3	94 ± 5
Change	-1 (-2, 1)	-1 (-3, 1)	0 (-2, 1)	-1 (-3, 0)
45 min-post	97 ± 4	93 ± 7	98 ± 3	95 ± 6
Change	-2 (-5, 0)	-3 (-5, 0)	0 (-1, 0)	0 (-2, 2)

Data are presented as mean ± standard deviation with change data presented as change from baseline; mean (95 % confidence interval).

greater extent on the outdoor trial (outdoors + 59 ms; indoors +8 ms; condition*time interaction, $t_{[4732]} = 2.19$; $P = 0.029$) (Fig. 1A). There was no difference between the trials regarding the pattern of change in response time 45 min post-physical activity (condition*time interaction, $P = 0.192$).

Complex Level: The pattern of change in response time was similar between the trials on the complex level of the Stroop test immediately post-physical activity (condition*time interaction, $P = 0.957$). However, the improvement in response time was greater on the outdoor trial 45 min post-physical activity (outdoors -94 ms; indoors -20 ms; condition*time interaction, $t_{[9108]} = -3.09$; $P = 0.002$) (Fig. 1B).

3.1.2. Stroop test- accuracy

Simple Level: The pattern of change in accuracy was similar between trials immediately post-(condition*time interaction, $P = 0.136$) and 45 min post- (condition*time interaction, $P = 0.185$) physical activity.

Complex Level: The improvement in accuracy was greater on the outdoor trial both immediately post- (outdoors +2 %; indoors +0.4 %; condition*time interaction, $z_{[9960]} = 2.096$; $P = 0.036$) and 45 min post- (outdoors: +2 %; indoors: +0.1 %; condition*time interaction, $z_{[9960]} = 2.03$; $P = 0.043$) physical activity (Fig. 1D).

3.1.3. Sternberg paradigm- response times

One-item level: The change in response time was similar between the outdoor and indoor trials immediately post-physical activity (condition*time interaction $P = 0.417$). At 45 min post-physical activity, response time improved in the outdoor trial (-9 ms) while slowing on the indoor trial (+73 ms) (condition*time interaction, $t_{[3582]} = -2.23$; $P = 0.026$) (Fig. 2A).

Three-item Level: Response time improved on the outdoor trial and worsened on the indoor trial both immediately post- (outdoor -34 ms; indoor +14 ms; condition*time interaction, $t_{[7137]} = -3.36$; $P = 0.001$) and 45 min post- (outdoor -37 ms; indoor +69 ms; condition*time interaction, $t_{[7137]} = -5.14$; $P < 0.001$) physical activity (Fig. 2B).

Five-item Level: The change in response time was similar between conditions both immediately post- (condition*time interaction, $P = 0.895$) and 45 min post- (condition*time interaction, $P = 0.073$) physical activity.

3.1.4. Sternberg paradigm- accuracy

1-item level: The change in accuracy was similar between trials both immediately post- (condition*time interaction, $P = 0.847$) and 45 min post- (condition*time interaction, $P = 0.706$) physical activity.

Three-Item Level: There was a similar change in accuracy between trials immediately post- (condition*time interaction, $P = 0.952$) and 45 min post- (condition*time interaction, $P = 0.365$) physical activity.

Five-Item Level: A similar change in accuracy was seen between trials immediately post- (condition*time interaction, $P = 0.190$) and 45 min post- (condition*time interaction, $P = 0.433$) physical activity.

3.1.5. Flanker task- response times

Congruent: Response time changed similarly in both trials immediately post-physical activity (condition*time interaction, $P = 0.257$). At 45 min post-physical activity, response time was improved to a greater extent in the outdoor trial compared to the indoor trial (outdoor -44 ms; indoor -14 ms; condition*time interaction, $t_{[7022]} = -3.47$; $P = 0.001$) (Fig. 3A).

Incongruent: There was a similar change in response time between trials immediately post-physical activity (condition*time interaction, $P = 0.197$). There was a slight (yet statistically insignificant) improvement in response time after the outdoor trial 45 min post-physical activity (outdoor -56 ms; indoor -39 ms; condition*time interaction, $t_{[6743]} = -1.90$; $P = 0.058$) (Fig. 3B).

3.1.6. Flanker task- accuracy

Congruent: The change in accuracy was similar between the trials both immediately post- (condition*time interaction, $P = 0.970$) and 45 min post- (condition*time interaction, $P = 0.216$) physical activity.

Incongruent: There was no difference in the change in accuracy between trials immediately post-physical activity (condition*time interaction, $P = 0.840$). At 45 min post-physical activity, accuracy was maintained following outdoor physical activity but reduced following

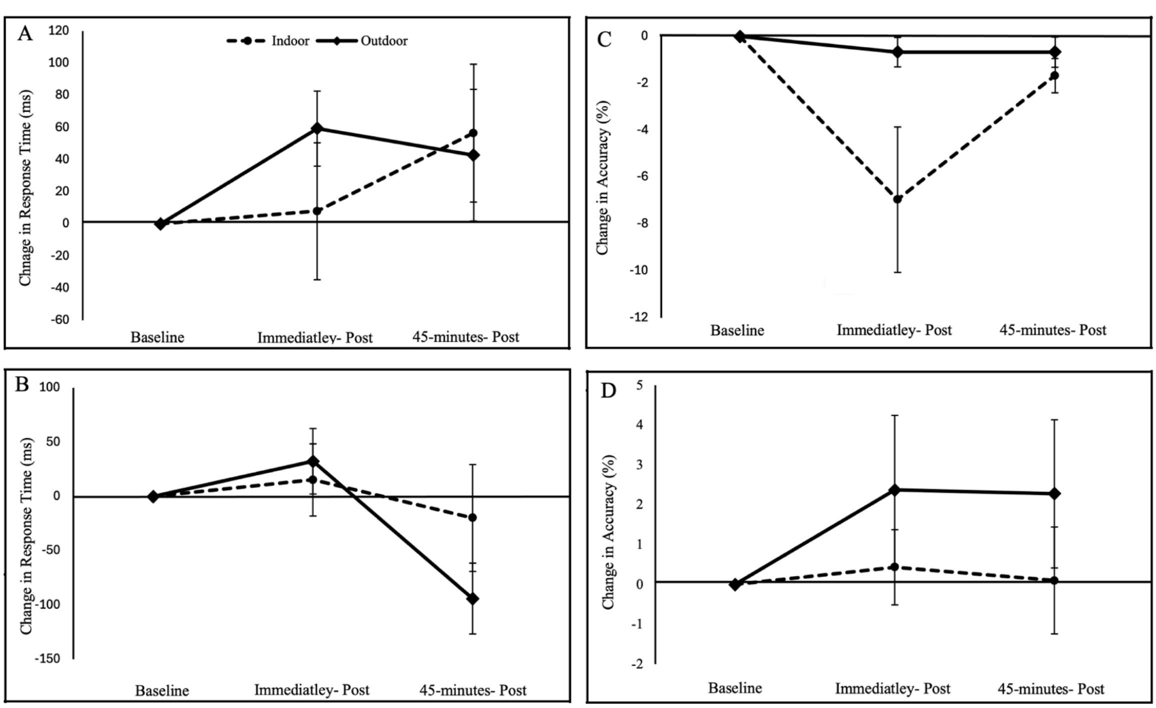

Fig. 1. Stroop test simple and complex level response time and accuracy change from baseline immediately post- and 45 min post-physical activity. Data are mean ± standard error of the mean. A. Stroop test simple change in response time; B. Stroop test change in complex response time; C. Stroop test change in simple accuracy; D. Stroop test change in complex accuracy.

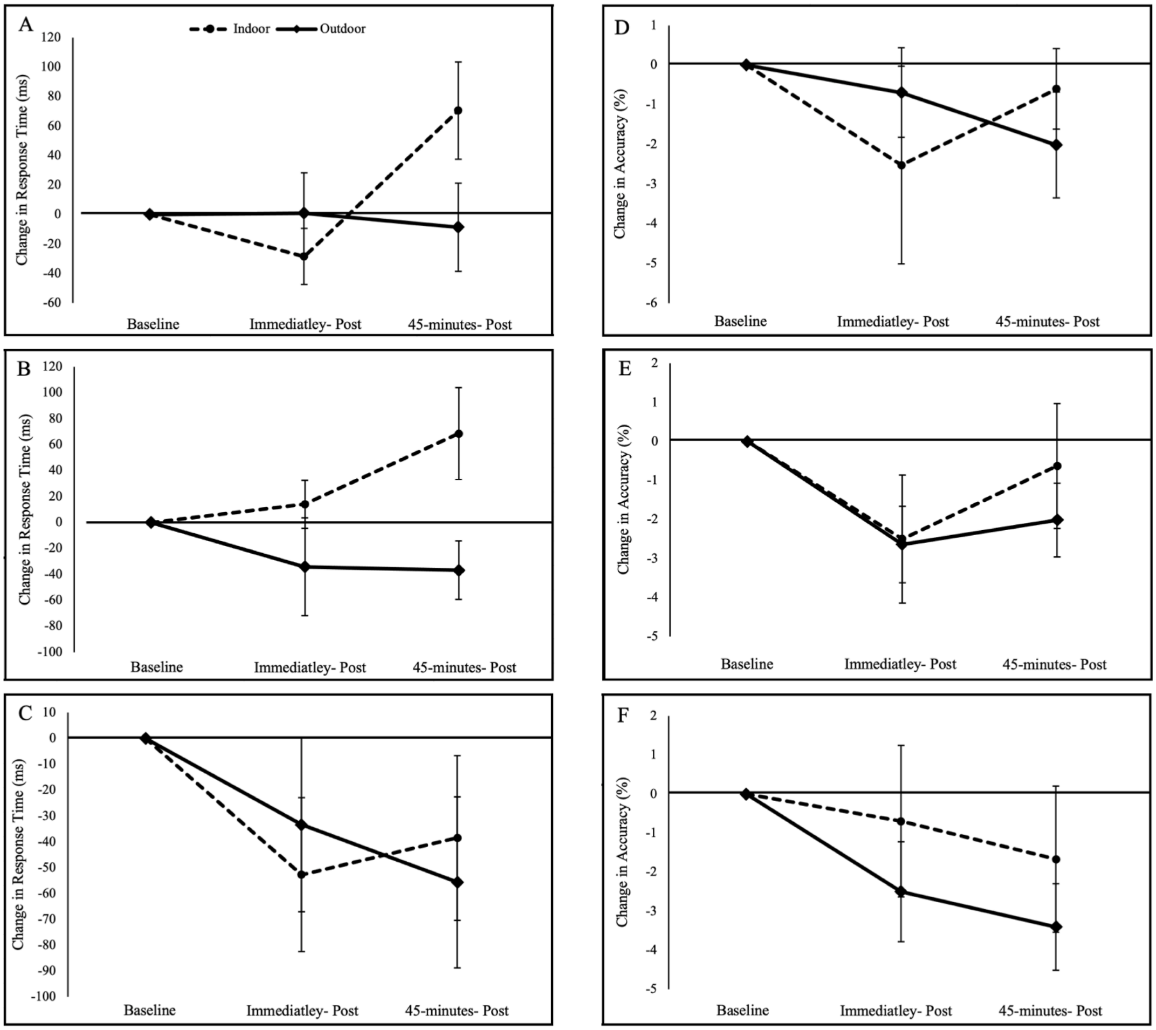

Fig. 2. Sternberg paradigm 1-item, 3-item, and 5-item level response time and accuracy change from baseline immediately post- and 45 min post-physical activity. Data are mean ± standard error of the mean. A. Sternberg paradigm 1-item change in response time; B. Sternberg paradigm change in 3-item response time; C. Sternberg paradigm 5-item D. Sternberg paradigm change in 1-item accuracy; E. Sternberg paradigm change in 3-item accuracy; F. Sternberg paradigm change in 5-item accuracy.

indoor physical activity (outdoor no change; indoor -3 %; condition*time interaction, $z_{[7367]} = 0.26$; $P = 0.008$) (Fig. 3D).

3.2. Physical activity enjoyment

There was no difference in the total physical activity enjoyment scale score between the outdoor and indoor sessions (69 ± 8 *vs* 70 ± 7), respectively; $P = 0.271$).

3.3. Physical activity characteristics

Average heart rate was significantly higher during the outdoor *vs* the indoor physical activity session (160 ± 28 *vs* 150 ± 13 beats·min^{-1}, respectively; $t_{[44]} = -2.67$; $P = 0.005$). Total distance covered was significantly lower in the outdoor *vs* the indoor physical activity session (1198 ± 478 m *vs* 1558 ± 327 m, respectively; $t_{[43]} = 4.89$; $P < 0.001$). The total number of sprints performed was also lower outdoor *vs* indoor (5 ± 7 *vs* 8 ± 9, respectively; $t_{[43]} = 0.01$; $P < 0.001$) (supplementary Table 2).

4. Discussion

The overarching finding of this present study was that a physical activity session performed outdoors significantly improves cognitive function more than when performed indoors. Specifically, when performed outdoors there were superior improvements in inhibitory control (Stroop test complex level accuracy), working memory (response time in the 1- and 3-item level of the Sternberg Paradigm), and attention (response time in the congruent and accuracy on the incongruent level of the Flanker test), compared to when the same physical activity session was performed indoors.

This is the first time such improvements in cognitive function have been seen following an outdoor, compared to an indoor, physical activity session. The findings of the present investigation conflict with a recent similar investigation (Wade et al., 2020 [39] which compared circuit-based physical activity performed indoors, in a park, and in nature, in older adolescents (aged 14 & 15 years). In this study by Wade et al. [39] sustained attention accuracy was increased following indoor physical activity compared physical activity performed in a park and there were no group-by-time effects on working memory. This conflicts with the findings of the present investigation where we demonstrated superior improvements in all cognitive domains assessed (inhibitory control, working memory, and attention) when physical activity was performed outdoors. The conflicting results may be the result of several important differences between Wade et al. [39] and the present investigation, including: the participant group (older adolescents aged 14–15

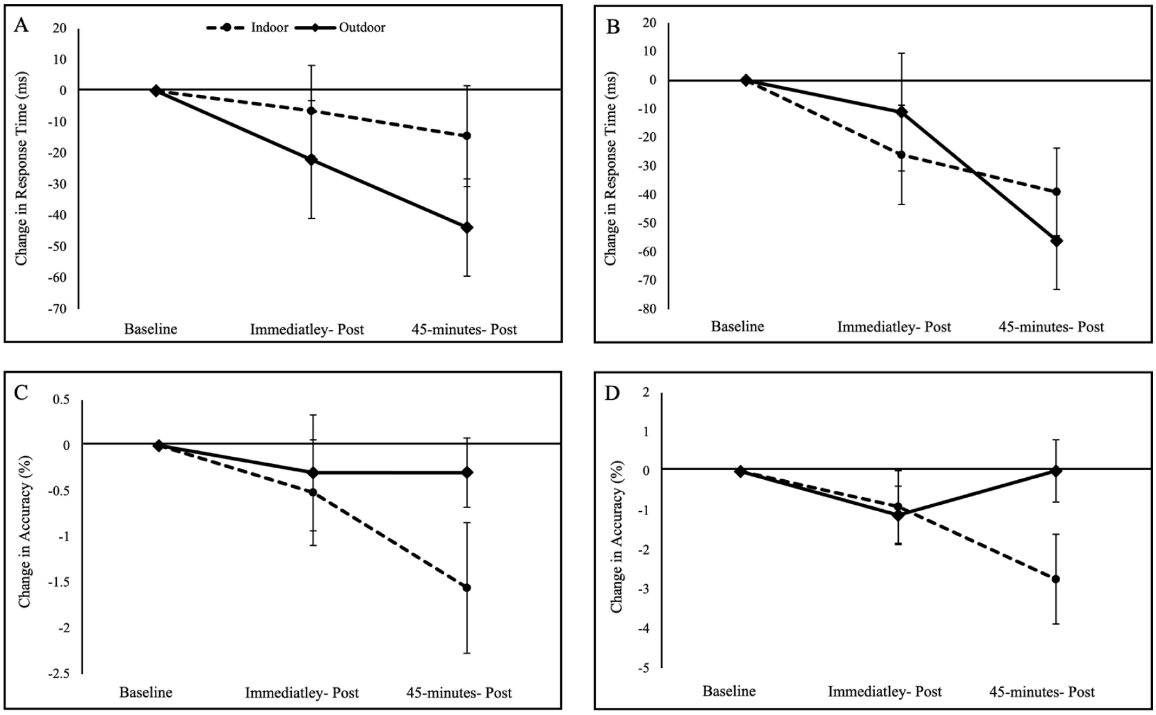

Fig. 3. Flanker test congruent and incongruent level response time and accuracy change from baseline immediately post- and 45 min post-physical activity. Data are mean ± standard error of the mean. A. Flanker test congruent change in response time; B. Flanker test change in incongruent response time; C. Flanker test change in congruent accuracy; D. Flanker test change in incongruent accuracy.

vs 11–13 years, respectively); cognitive function assessment (only performed twice [pre- and 6 min post-physical activity], compared to three times [pre-, immediately-, and 45 min post-physical activity], respectively); physical activity modality (circuit-based *vs* team-based, respectively); physical activity intensity (average heart rate was slightly lower for all sessions in Wade et al. [39]); and physical activity duration (21- *vs* 30 min). These differences between the two investigations may cause conflicting results because all these factors have been suggested to be moderators in the exercise-cognition relationship [45]. Nonetheless, the present study provides important findings by comparing the same physical activity session performed indoors and outdoors; and provides novel findings that outdoor physical activity is superior for cognition.

In the present investigation, the benefits of outdoor physical activity were evident for all cognitive domains. This is in line with literature reporting such overarching cognitive benefits of nature and physical activity independently. Nguyen & Walters [46] reported significant positive effects of various nature interventions on attention and executive function in children and adolescents while Haverkamp et al. [22] highlighted the favourable impacts of physical activity on various cognitive function domains. However, the present study is the first to suggest a synergistic effect of the outdoor environment and physical activity on cognitive function. Synergistic effects of nature and physical activity have been reported for other outcomes including negative emotions [47], self-esteem and mood [48,49], and cognitive ability [50]. However, this research has largely been conducted with college students, with similar investigations in children and adolescents lacking. Regarding the potential synergetic effects of physical activity and nature, there have been two primary mechanistic theories suggested to explain how nature exposure improves cognitive function. The first is Attention Restoration Theory [33]. This theory suggests that exposure to nature can replenish cognitive resources by capturing attention in a non-taxing way which allows time for cognitive processes to be restored. It is suggested that this shift in cognitive engagement helps replenish depleted mental resources and thus evokes a restorative effect which revitalises attentional capacity and reduces mental fatigue. Adolescents spend a substantial amount of time in activities that require prolonged and focused attention (for example, in school), which can lead to mental fatigue and diminished capacity to carry out complex cognitive tasks [51,52], thus making them susceptible to the detriments of cognitive overload and fatigue [53]. Thus, exposure to nature offers an organic, practical, and cost-effective avenue to nurture and support healthy cognitive development during these critical formative years. A second proposed mechanism is stress reduction theory (proposed by Ulrich, [54]), which suggests that a positive emotional response to natural environments reduces stress and negative affect while increasing positive affect. It is proposed that the reductions in negative affect and stress then allow a person to maintain higher levels of sustained attention, which leads to cognitive benefits [54]. However, a recent meta-analysis [55] showed that mood effects are not correlated with cognitive benefits thus counteracting the idea that mood changes drive the cognitive effects as suggested by stress reduction theory. The findings of the present study are in line with this meta-analysis as we showed an improvement in cognitive function when physical activity was performed outdoors compared to indoors, despite no differences in perceived levels of enjoyment between the sessions.

When interpreting the greater enhancements in cognitive function following outdoor physical activity, the differences in physical activity metrics and relative exercise intensity should also be considered. During the outdoor physical activity session participants covered a smaller total distance and performed less sprints (physical activity metrics), however they had a higher average heart rate (relative exercise intensity). These objective measures of physical activity intensity suggest that natural differences were present within the physical activity sessions despite identical session plans, timings, equipment, court dimensions, group sizes, individuals in each group, time of day etc. This is something that should therefore be considered when interpreting the cognitive function outcomes; the marginally higher relative exercise intensity (higher average heart rate) during the outdoor physical activity session may have facilitated superior cognitive performance. However, this is speculative, and further work should be conducted to fully examine this relationship between relative exercise intensity and cognitive benefits following physical activity.

4.1. Strengths, limitations and future research directions

The methodology of the present study is an integral strength, particularly with regard to how factors were controlled to ensure that the only moderating factor between the two trials was the environment (indoors/ outdoors). This involved implementing several measures that ensured that all physical activity sessions were identical in every way except the environment (indoor or outdoor). This included matching all of the following in each session: the time of day the trials were conducted, the room used for temporary laboratory, protocol timings, the laptop used by each participant, the group size, the participants in each group, the HR and GPS monitors worn by each participant, the physical activity drills, the order of the physical activity drills, the timings of the physical activity drills, the court dimensions used for the physical activity drills, the equipment for the physical activity drills (including basketball nets and basketballs), and the lead investigator (who ran the sessions and led the physical activity session). The monitoring of physical activity intensity (participant load and absolute physical activity characteristics), recorded via chest mounted combined GPS and heart rate, also adds to the rigorous methodology of this investigation as it enabled physical activity intensity to be analysed post-testing to identify whether physical activity intensity was similar between the conditions.

However, the present study is not without limitation. For example, the present study was conducted in only two schools (two groups per school), both of which are in relatively rural areas. An abundance of literature proposes a significant benefit of green space over built environments for cognitive, mental, and physical outcomes. Had we also used an inner-city school, for example, where there was less (or no) green space there would have been the opportunity to compare the effects in different outdoor environments, as some literature has suggested that exercising in more ‘natural’ environments as opposed to more synthetic/ urban ones is more beneficial for well-being and mood responses [56], and in particular may lower negative emotions, such as anger and sadness [57]. However, evidence on this is inconsistent, especially with regard to cognitive function in children and young people, and therefore requires substantially more research to explore this. A further limitation of this study is the relatively narrow age range (age 11–13 years) of participants. Future research should consider whether older adolescents who are in the process of completing their general education qualifications (typically around age 16 years) may see an even larger benefit of outdoor physical activity than younger children. These older adolescents are more likely to spend more time in tasks that involve prolonged attention and therefore are more likely to become mentally fatigued. According to attention restoration theory, it could be suggested that the benefits of performing physical activity outdoors may be even larger for these adolescents. This again is an avenue of research that requires focus in future investigations. Further to this, while this study examined objective physical activity intensity (heart rate and GPS) it did not examine subjective physical activity intensity (rating of perceived exertion [RPE]), this is something that would have been interesting to examine, especially in combination with the PACES and the objective physical activity measures given that other studies have demonstrated that higher intensity activities, such as high intensity interval training, have been shown to elicit higher ratings of pleasure (PACES) despite higher RPE and objective physical activity intensity [58]. Combined, these factors may be able to further explain cognitive differences following indoor and outdoor physical activity.

5. Conclusions

This is the first study to demonstrate the cognitive benefits of outdoor physical activity in secondary school children. To ensure identical replication of trails several measures were implemented, doing so provides confidence that difference in cognitive function outcomes observed are the result of the environmental conditions only and not other differences between the trials. From combined GPS and heart rate monitor recordings it was evident that activity level (total distance covered and total number of sprints performed) was higher during the indoor session, yet cognitive function was improved more in the outdoor session; demonstrating that the superior cognitive benefits observed following outdoor physical activity were not the result of more activity being performed during the outdoor session. This also provides a novel finding in that when the same planned session was delivered outdoors and indoors, participants naturally performed more activity when indoors. This could be of interest to those designing future physical activity interventions.

CRediT authorship contribution statement

Grace Walters: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karah J. Dring:** Investigation. **Ryan A. Williams:** Writing – review & editing, Investigation. **Robert Needham:** Investigation. **Simon B. Cooper:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization.

Conflicts of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.physbeh.2025.114888.

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