The Effects of a Mid-Morning Bout of Exercise on Adolescents' Cognitive Function

Abstract

The aim of the present study was to examine the effects of a mid-morning bout of exercise on adolescents' cognitive function in a randomised crossover design where each participant completed two experimental trials. Forty-five adolescents (13.3±0.3 years old), undertook a bout of exercise (ten repeats of level one of the multi-stage fitness test, 30 s rest between repeats; exercise trial) or continued to rest (resting trial). A battery of cognitive function tests assessing visuo-motor speed, executive function and working memory (visual search test, Stroop test and Sternberg paradigm, respectively) was completed 30 min before and 45 min following the exercise.

Average heart rate during exercise was 172±17 beats/min. On the visual search test, there was a greater improvement in response times across the morning on the exercise trial ($t=2.6$, $p=0.009$). However, this improvement in response times was combined with a greater decrease in accuracy on the exercise trial ($z=2.0$, $p=0.044$). On the Sternberg paradigm there was a greater improvement in response times across the morning following exercise when compared to resting ($t=2.6$, $p=0.010$). The mid-morning bout of exercise did not affect Stroop test performance.

These improvements in response times are most likely the result of a general speeding up of responses across several cognitive domains, because response times were improved similarly across two different domains and across all test complexity levels, rather than being restricted to the specific high cognitive load levels. Accordingly, exercise in school settings may help to improve cognitive function in adolescents during the school morning.

Keywords: acute exercise; executive function; youth; attention; working memory; visual search

1. Introduction

There is increasing evidence that an acute bout of exercise enhances cognitive function in adult populations (Lambourne & Tomporowski, 2010; Chang, Labban, Gapin, & Etnier, 2012), but few studies focus on young people. There is some evidence to suggest that exercise is also beneficial for cognitive function in young people (Best, 2010; Ellemberg & St-Louis-Deschênes, 2010; Hillman, et al, 2009; Stroth et al, 2009). This suggestion is confirmed by the meta-analysis of Sibley & Etnier (2003), indicating an overall effect size (ES) of 0.32 for the relationship between exercise and function in a wide range of cognitive domains in young people. Age of the participants was found to be an important moderator, with the largest effect size for 'middle school' students aged 8-11 (ES = 0.48), and a smaller ES (0.24) for 'high school' students aged 12-16 (Sibley & Etnier, 2003). In the later meta-analysis of Chang et al (2012), age was also a moderator of the relationship between exercise and cognitive function. Converse to the findings of Sibley & Etnier (2003), a larger effect size was observed for 'high school' (aged 14-17) than for 'elementary school' (aged 6-13) children (ES = 0.17 vs. 0.07). Such fluctuations in effect size may result from differences in methodology, for example the inclusion of different age ranges in each category and pooled data from largely from unpublished studies. However, they may also point to a more fundamental role of age in modifying the effects of exercise on cognitive function, and accordingly it is important to investigate this relationship specifically in young people.

Theoretical support for this view is based on the rapid growth and changes in metabolism in adolescents, thus their responses to exercise may be different (Cromer et al, 1990; Kanarek, 1997). For example, the findings in younger children (aged 6-11) (Ellemberg & St-Louis-Deschênes, 2010; Hillman, et al, 2009; Stroth et al, 2009) may not generalise to adolescents, given that younger children have a larger brain weight relative to their body weight and a 50% greater metabolic rate per unit of brain weight (Hoyland, Dye, & Lawton, 2009). In the small number of published studies on adolescents there is a general trend towards exercise having a beneficial effect on adolescents' cognitive function (e.g. Budde, Voelcker-Rehage, Pietraβyk-Kendziorra, Ribeiro, & Tidow, 2008; McNaughten & Gabbard, 1993; Travlos, 2010; Zervas, Danis, & Klissouras, 1991). Some early studies assessed cognitive function following Physical Education lessons and findings include greater accuracy of attention following a PE lesson during a normal science lesson (Zervas et al, 1991). Furthermore, mathematical computation was greater following moderate intensity walking when compared with a resting control group (McNaughten & Gabbard, 1993).

Most of these studies have assessed performance on complex cognitive operations, involving contributions from several more basic cognitive domains such as executive function and working memory. Several theories postulate a differential impact of exercise on such basic cognitive functions, because they rely on different brain regions which in turn may respond differently to exercise. Whilst early theories suggested that complex information processing is most affected, the executive function hypothesis (Churchill et al., 2002; Kramer, Colcombe, McAuley, Scalf & Erickson, 2005), argues that executive function (e.g. the ability to plan and initiate goal-directed behaviour and suppress undesired responses) benefits most from exercise. Other authors have found that a test of working memory (digit span) is most sensitive to exercise effects (Hogervorst, Clifford, Stock, Xin & Bandelow, 2012). Differential effects of exercise on the basic components of cognitive function thus remain plausible but controversial.

Accordingly, in the present study we aim to investigate the effects of exercise on three basic cognitive domains: executive function (which includes aspects of attention and inhibition of automatic responses), working memory and visuo-motor speed. Each of the basic cognitive functions investigated here may respond differently to exercise, in which case one could conclude that exercise has differential effects on specific cognitive functions and probably also on different brain areas. Conversely, if exercise effects are found to apply similarly across all the cognitive tests, one may conclude that a more general mechanism is at work, with comparable effects throughout the brain.

Where positive effects on cognitive function have been seen following exercise, several mechanisms have been postulated to mediate such effects, including increased cerebral blood flow (Querido & Sheel, 2007) which enhances the delivery of glucose and oxygen to neural tissues and the clearance of carbon dioxide (Jorgensen, Nowak, Ide, & Secher, 2000). Such a mechanism may result in regionally specific effects on the brain, which could be detected in the current study via different effects on the three cognitive function tests. However, it has also been suggested that more general arousal mechanisms may be at work, whereby exercise increases physiological and/or cognitive arousal, increasing the allocation of resources to the cognitive task and thus, enhancing cognitive function (Brisswalter, Collardeau, & René, 2002). A more generic effect on arousal would in turn be more likely to affect various basic cognitive functions equally, in which case the current study would be more likely to yield a pattern of results that shows similar effects of exercise on all the cognitive function tests. In addition, all the cognitive tests employed here contain at least two levels with different cognitive loads and if exercise were to affect all cognitive load levels equally again this would suggest a more generic effect.

A limitation of the studies conducted in adolescents to date is that cognitive function has been measured immediately (or very soon, i.e. < 10 min) following exercise. However, in everyday school settings, it may be up to one hour between exercise (at break time or during a PE lesson) and the next academic lesson, where cognitive function is of interest for learning. Indeed, in adults, whilst it was hypothesised that the effects of exercise may decline with increasing time between the exercise period and cognitive testing, the effect sizes were similar across different lengths of time between exercise and cognitive testing (Lambourne & Tomporowski, 2010). However, this has not been examined in adolescents.

Therefore, the aim of the present study is to address this void in the literature and examine the effects of exercise (which could easily be incorporated into the school morning, e.g. at break time) on subsequent cognitive function in adolescents. This study will use a battery of cognitive function tests (visual search test, Stroop test and Sternberg paradigm), to assess several basic components of cognitive function. Based on the limited evidence available to date, the authors hypothesise that cognitive function will be enhanced following an acute bout of exercise, but the previous literature is equivocal as to whether or not this will be a test specific or generalised response.

2. Methodology

2.1: Participant Characteristics

Sixty schoolchildren aged 12 to 13 years were recruited to participate in the study. However, 15 participants failed to complete the study because they were either absent from school for one of the experimental trials (n = 11) or failed to comply with the dietary control conditions (n = 4). During familiarisation, simple measures of height, body mass and waist circumference were taken. Height was measured using a Leicester Height Measure (Seca, Hamburg, Germany), accurate to 0.1 cm. Body mass was measured using a Seca 770 digital scale (Seca, Hamburg, Germany), accurate to 0.1kg. These measures allowed the determination of Body Mass Index (BMI), calculated by dividing body mass [kg] by the square of the height [m^2]. Waist circumference was measured at the narrowest point of the torso between the xiphoid process of the sternum and the iliac crest, to the nearest 0.1cm. For descriptive purposes, the anthropometric characteristics of the participants who completed the study (n = 45) are provided in table 1. According to age-referenced cut-offs (Reilly & Wilson, 2006), 33% of participants were overweight (>85th centile) and 11% were obese (>95th centile).

(Insert table 1 here)

2.2: Study Design

The study was approved by the institutions ethical advisory committee. Participants were recruited from a local secondary school and in accordance with the ethical guidelines of the British Education Research Authority for school based research, school level consent was obtained from head teachers. In addition, written parental informed consent was obtained and a health screen questionnaire completed (covering any medical issues relating to the child) to ensure all participants were in good health.

Each participant undertook a familiarisation session, which preceded the first of two experimental trials by seven days. During familiarisation, the protocol of the study was explained and participants were provided with an opportunity to familiarise themselves with the methods involved, which included completing the battery of cognitive function tests. In addition, participants were provided with an opportunity to ask questions and clarify any part of the tests they did not fully understand.

The study employed a randomised crossover design, with participants blind until arrival at school on each day of testing. The experimental trials consisted of an exercise trial and a resting trial. Therefore, participants acted as their own controls. Trials were scheduled seven days apart and participants reported to school at the normal time. The experimental protocol is shown in figure 1.

(Insert figure 1 here)

2.3: Dietary Control

Participants consumed a meal of their choice the evening before their first experimental trial and were asked to repeat this meal for their subsequent trial. Following this meal, participants were asked to observe an overnight fast from 10pm. In order to maintain euhydration, participants were allowed to drink water *ad libitum* during this time. In addition, participants were asked to avoid any unusually vigorous exercise for 24 h prior to each experimental trial. Prior to each main trial, a telephone call was made to participants' parents to remind them of this information. Participants who had not followed these requirements were removed from the study (n = 4).

2.4: Exercise Protocol

The exercise performed was a modified version of the Multi-Stage Fitness Test (MSFT, National Coaching Foundation, UK). The exercise protocol was 10 minutes in duration and consisted of 10 repetitions of stage one (each consisting of 7 x 20 m shuttle runs at 8.0 $km.h^{-1}$), with a 30 s rest between each repetition. Prior to the exercise, participants were fitted with a Polar Wearlink heart rate monitor and a Polar S610i watch (Polar, Finland). Immediately following each repetition, if heart rate had reached 190 $beats.min^{-1}$ (approximately 90% of maximum heart rate in this population), participants were instructed to stop running and to walk for the remainder of the test. The duration of the exercise was chosen so it was sufficiently brief to fit into a normal school morning and reflected adolescents' usual physical activity patterns. Consequently, the exercise protocol could be incorporated into a school morning and potentially has practical application, especially given the well documented social, emotional, physical and health benefits of break time/recess to young people (for review see Ramstetter, Murray, & Garner (2010)).

Of the 45 adolescents who completed the study, 23 (51.1%) completed all 10 repeats of level one of the MSFT without their heart rate reaching the threshold of 190 beats.min^{-1}. Overall, participants ran for 7 ± 1 min (mean ± S.D.) and whilst running, the average heart rate was 178 ± 11 beats.min^{-1}. The participants whose heart rate reached 190 beats.min^{-1} continued to walk for the remainder of the exercise, during which their heart rate was 151 ± 16 beats.min^{-1}. However, the total exercise time (running and walking) for all participants was 10 min, with an overall average heart rate of 172 ± 17 beats.min^{-1}.

2.5: Capillary Blood Sampling

Capillary blood samples have previously been used successfully in a similar study population (Cooper, Bandelow, & Nevill, 2011) and were preferred to venous blood samples in the present study due to ethical constraints in young people. The participants' hands were warmed via submersion in warm water to increase capillary blood flow. A Unistik single use lancet (Unistik Extra, 21G gauge, 2.0mm depth, Owen Mumford Ltd., UK) was used and the blood collected into two 300 µl EDTA coated microvettes (Sarstedt Ltd., UK). Two 25 µl whole blood samples were removed using plain pre-calibrated glass pipettes (Hawksley Ltd., UK), immediately deproteinised in 250 µl of 2.5% ice cooled perchloric acid in 1.5 ml plastic vials and centrifuged at 7000 rpm for 4 minutes (Eppendorph 5415C, Hamburg, Germany). The remaining whole blood was also centrifuged at 7000 rpm for 4 minutes (Eppendorph

5415C, Hamburg, Germany) and the plasma removed and placed into 500 µl plastic vials. All samples were frozen at -20 ºC until analysis.

Blood glucose concentrations were determined using a commercially available kit (GOD-PAP method, GL 2610, Randox, Ireland) and were read photometrically using a Cecil CE393 digital grating spectrophotometer (Cambridge, UK). Plasma insulin concentrations were determined using an enzyme-linked immuno-sorbent assay (ELISA) (Mercodia Ltd., Sweden). Blood lactate concentrations were determined using the method described by Maughan (1982).

2.6: Mood Questionnaire

The mood questionnaire was a modified version of the 'Activation-Deactivation Check List' (AD ACL) short form, which has previously been shown as both a valid and reliable measure of mood (Thayer, 1986). The 20 item questionnaire was split into four components of mood; energy, tiredness, tension and calmness, each having five corresponding adjectives on the questionnaire. The original AD ACL short form was piloted in an adolescent population and subsequently five of the adjectives were changed to ensure suitability for the study population, with the modified version being previously used successfully in a similar study population (Cooper et al, 2011). The adjectives used and their corresponding components of mood were; energy: active, energetic, alert, lively and wide-awake; tiredness: sleepy, tired, drowsy, exhausted and fatigued; tension: anxious, nervous, fearful, worried and tense; and calmness: restful, calm, at-rest, laid-back and quiet. The scoring system was also slightly modified, with participants asked to respond on a scale of 1 to 5 regarding how they felt at that moment in time (where 1: definitely do not feel, 3: unsure, 5: definitely feel). The scores on the adjectives for each component of mood were summed, providing an overall score for each component.

In addition, three visual analogue (VAS) scales were used to provide a measure of participants' hunger, fullness and concentration. The VAS scales consisted of a 10 cm line from one extreme to the other (i.e. not at all to very), with participants indicating the point on the line that applied to them at that moment in time.

2.7: Cognitive Function Tests

The battery of cognitive function tests was administered via a laptop computer and lasted approximately 15 min. The battery of tests included a test of visual search, a Stroop test and the Sternberg paradigm. Written instructions appeared on the screen at the start of each test, which were repeated verbally by an investigator. Each cognitive function test was preceded by 3-6 practice stimuli, where feedback was provided regarding whether the participants' response was correct or not. Data from these practice stimuli were discarded and once the test started no feedback was provided. The cognitive function tests were administered to groups of 10-12 participants at any one time, in silence and separated such that participants could not interact with each other during the cognitive testing. The same testing procedure has been previously used successfully in a similar study population (Cooper et al, 2011) and the tests were administered in the order they are described here.

2.7.1: Visual Search Test

The visual search test consisted of two test levels, each consisting of 21 stimuli. On each test level, participants were instructed to respond as quickly as possible to the stimuli by pressing the space bar on the keyboard. In both test levels there were 21 different locations for the stimuli, with the order of the locations randomised.

The stimuli in the baseline level were triangles drawn in solid green lines on a black background, providing a measure of simple visuo-motor speed. The complex level had random green dots covering the screen, which were redrawn every 250 ms to induce the visual effect of a flickering background, acting as a background distractor. The target triangles were drawn with a few dots on each line and the density of these dots increased until the participant responded (the lines becoming denser until a response was registered). This provided a measure of complex visual processing. The variables of interest on both levels were the response times of correct responses and the proportion of correct responses made.

2.7.2: Stroop Test

The Stroop test measures the sensitivity to interference and the ability to suppress an automated response (i.e. the time required to identify the colour rather than read the word) (Stroop, 1935) and is a commonly used measure of selective attention (van Zomeren & Brouwer, 1992). The Stroop test consisted of two levels. Both levels involved the test word being placed in the centre of the screen, with the target and distractor presented randomly on the right or left of the test word. The target position was counterbalanced for the left and right side within each test level. The participant was asked to respond as quickly as possible, using the left and right arrow keys, to identify the position of the target word.

The baseline level contained 20 stimuli, where the test word was printed in white on the centre of the screen and the participant had to select the target word, from the target and distractor, which were also printed in white. The colour-interference level contained 40 stimuli and involved the participant selecting the colour the test word was written in, rather than the actual word (which was an incongruent colour), again using the right and left arrow keys to identify the target. The choices remained on the screen until the participant responded. The variables of interest were the RT of correct responses and the proportion of correct responses made.

2.7.3: Sternberg Paradigm

The Sternberg Paradigm (Sternberg, 1969) is a test of working memory and has three levels. Each test level presented a different working memory load; one, three or five items. On the baseline (number) level, the target was always the number ‘3’. This level contained 16 stimuli and provides a measure of basic information processing speed. The three- and five-item levels had target lists of three and five letters respectively, each containing 32 stimuli.

At the start of each level, the target items were displayed together with instructions to press the right arrow key if the stimulus was a target item and the left arrow key otherwise. The correct responses were counterbalanced on each level between the right and left arrow keys. The choice stimuli were presented on the centre of the screen with an inter-stimulus interval (ISI) of 1 second, during which the screen was blank. The choices remained on the screen until the participant responded. The variables of interest were the RT and the proportion of correct responses made.

2.8: Breakfast

A range of breakfast foods were provided for participants on their first trial, from which they chose ad libitum. The quantity of food taken by each participant was recorded and any leftovers weighed using a Salter 1029 WHDRT scale (Salter, Hamburg, Germany) to allow determination of the breakfast consumed by each participant. Due to the well documented effect of breakfast consumption and composition on adolescents' cognitive function (Hoyland et al, 2009; Cooper et al, 2011), on the subsequent trial, an identical breakfast was provided along with instructions that all the breakfast must be consumed within 15 min. All participants followed this instruction. The breakfast consumed consisted of (mean ± SD): 397±172 kcal, 76.4±34.5 g of carbohydrate, 8.1±3.8 g of protein and 6.4±4.1 g of fat.

2.9: Statistical Analysis

The mood, blood glucose, plasma insulin and blood lactate data were analysed using PASW statistics (Version 18, SPSS Inc., Chicago, Il, USA) via two-way, trial (exercise /resting) by session time (0/30/60/120 min), analysis of variance (ANOVA) for repeated measures. Effect sizes (ES) are presented as partial eta squared values (η^2). In addition, where paired comparisons were conducted, analysis used a paired samples t-test, with ES presented as Cohen's d. Data are presented as mean ± S.E.M..

The cognitive function data were analysed using R (www.r-project.org, version 2.9.1). Response time analyses were performed using the nlme package for R, which implements mixed effect models. Accuracy analyses were performed with the lme4 package for R, which implements mixed effect models with non-normal outcome data distributions, similar to generalised linear models. Accuracy data analyses assumed a binomial outcome data distribution to best account for the binary (correct/incorrect) nature of the data. Analyses were conducted using a three-way trial (exercise/resting) by session time (9.30am/11.00am) by test level (baseline/complex) interaction and where appropriate, a two-way trial by session time analysis was conducted. ES are presented as raw effect sizes (ms or percentage of correct responses). For all analyses, significance was set as $p < 0.05$.

3. Results

3.1: Trial order balance

To minimise the influence of possible learning effects on the results, trial order was counterbalanced across participants. However, with drop-outs (n = 11 due to absence from school and n = 4 due to failing to comply with the overnight fast) the final dataset included 20 participants that had completed the resting trial followed by the exercise trial, and 25 participants with the reverse trial order. Rather than removing valid data points to arrive at a fully counterbalanced set of trial orders, possible order effects were corrected for statistically by including repeat test session number as a numerical co-variate, including linear and quadratic effects, where significant.

3.2: Cognitive Function Tests

For all cognitive tests the response times were first log transformed to normalise the distributions, which exhibited the right-hand skew typical of human response times. According to task complexity, minimum and maximum response time cut-offs were set to exclude those responses that can be considered anticipations and delayed responses. As such, minimum response time cut-offs were set at 300 ms for the visual search test, 250 ms for the Stroop test and 200 ms for the Sternberg paradigm. Maximum response time cut-offs were set at 1500 ms (baseline level) and 10000 ms (complex level) for the visual search test, 2500 ms (baseline level) and 4000 ms (complex level) for the Stroop test and 2000 ms (all levels) for the Sternberg paradigm. Only the response times of correct responses were used for response time analysis across all three cognitive tests.

3.2.1: Visual Search Test

Response Times: There was a significant three-way interaction for response times on the visual search test (trial by session time by test level interaction, $t_{(3,7301)} = 2.6$, $p = 0.009$, ES = 301 ms, figure 2). Upon inspection of figure 2, response times increased by a similar magnitude across the morning on the exercise and resting trials on the baseline level (trial by session time interaction, $p = 0.131$, figure 2a). However, on the complex level, whilst response times were slower at 9.30 am on the exercise trial, response times improved by a greater amount across the morning on the exercise trial, when compared to the resting trial (trial by session time interaction, $t_{(2,3677)} = 3.7$, $p < 0.001$, ES = 410 ms, figure 2b).

(Insert figure 2 here)

Accuracy: There was also a significant three-way interaction for accuracy on the visual search test (trial by session time by test level interaction, $z_{(3,7978)} = 2.0$, $p = 0.044$, ES = 2.7%, figure 3). Upon inspection of figure 3, accuracy decreased by a similar amount across the morning on the exercise and resting trials on the baseline level (trial by session time interaction, $p = 0.499$, figure 3a). However, on the complex level, whilst accuracy was greatest at 9.30 am on the exercise trial, there was a greater decrease in accuracy across the morning on the exercise trial, when compared to the resting trial (trial by session time interaction, $z_{(2,2966)} = 2.0$, $p = 0.046$, ES = 3.8%, figure 3b).

(Insert figure 3 here)

3.2.2: Stroop Test

Response Times: There was no difference in the pattern of change in response times across the morning between the exercise and resting trials (trial by session time interaction, p = 0.109); nor was this effect different between the baseline and complex levels (trial by session time by test level interaction, p = 0.135).

Accuracy: There was no difference in accuracy across the morning between the exercise and resting trials (trial by session time interaction, p = 0.307); nor was this effect different between the different test levels (trial by session time by test level interaction, p = 0.440).

3.2.3: Sternberg Paradigm

Response Times: The pattern of change in response times across the morning was not different on the exercise and resting trials between the different test levels (trial by session time by test level interaction, p = 0.838). However, across all test levels, whilst response times on the Sternberg paradigm improved across the morning on the exercise trial, they slowed across the morning on the resting trial (trial by session time interaction, $t_{(3,12607)} = 2.6$, p = 0.010, ES = 12 ms, figure 4).

(Insert figure 4 here)

Accuracy: There was no difference in accuracy across the morning between the exercise and resting trials (trial by session time interaction, $p = 0.833$), nor was this effect different between the different test levels (trial by session time by test level interaction, $p = 0.199$).

3.3: Mood

Each dimension of mood assessed by the modified ADACL (energy, tiredness, tension and calmness) improved during the first 30 min of the trials (when breakfast was consumed), then remained similar until the end of the trials (main effects of time; energy: $F_{(3,132)} = 16.4$, $p < 0.001$, $\eta2 = 0.272$; tiredness: $F_{(3,132)} = 19.1$, $p < 0.001$, $\eta^2 = 0.303$; tension: $F_{(3,132)} = 5.2$, $p = 0.004$, $\eta2 = 0.256$; calmness: $F_{(3,132)} = 13.1$, $p < 0.001$, $\eta2 = 0.229$). However, the pattern of change in each dimension of mood was the same across the morning between the exercise and resting trials (trial by session time interactions, all $p > 0.05$).

As with the aforementioned dimensions of mood, there was a consistent effect of the time of morning on hunger, fullness and concentration, as assessed by the VAS scales. The main changes coincided with the consumption of breakfast during the first 30 min of the trials, where hunger decreased, whilst fullness and concentration increased, before all three dimensions remained similar from 30 to 120 min during the rest of the trial (main effects of time; hunger: $F_{(3,114)} = 90.1$, $p < 0.001$, $\eta2 = 0.703$; fullness: $F_{(3,114)} = 104.3$, $p < 0.001$, $\eta2 = 0.733$; concentration: $F_{(3,114)} = 36.7$, $p < 0.001$, $\eta2 = 0.491$). However, the pattern of change in hunger, fullness and concentration across the morning was not different between the exercise and resting trials (trial by session time interactions, all $p > 0.05$).

3.4: Capillary Blood Samples

Blood glucose, plasma insulin and blood lactate concentrations were similar between the exercise and resting trials at 0, 30 and 60 min (all $p > 0.05$), but were significantly higher at 120 min on the exercise trial compared to the resting trial (blood glucose: $t_{(1,44)} = 3.8$, $p < 0.001$, $d = 0.569$; plasma insulin: $t_{(1,44)} = 2.3$ $p = 0.024$, $d = 0.349$; blood lactate: $t_{(1,44)} = 3.0$, $p = 0.005$, $d = 0.446$). These effects produced significant trial by session time interactions for all variables, where although the responses were similar between trials from 0 to 60 min, at 120 min blood glucose, plasma insulin and blood lactate concentrations were better maintained on the exercise trial, whereas they continued to decrease on the resting trial (trial by session time interactions: blood glucose: $F_{(3,132)} = 8.4$, $p < 0.001$, $\eta 2 = 0.161$, figure 5; plasma insulin: $F_{(3,132)} = 3.7$, $p = 0.014$, $\eta 2 = 0.077$, figure 6; blood lactate: $F_{(3,132)} = 2.9$, $p = 0.038$, $\eta 2 = 0.062$, figure 7).

(Insert figures 5, 6 & 7 here)

4. Discussion

The aim of the present study was to examine the effects of an acute bout of exercise (which could easily be incorporated into the school morning) on subsequent cognitive function in adolescents. Exercise improved response times in the Sternberg working memory task. However, all three working memory load levels of the Sternberg paradigm exhibited similar improvements in response times following exercise. These results suggest a generic effect of exercise that results in broadly improved response times across several cognitive domains. Participants were also slower but more accurate pre-exercise on the complex level of the visual search test, whilst post-exercise response times and accuracy were similar to those on the resting trial. The lack of an exercise effect on the Stroop test was probably related to test sensitivity, because the baseline level of the Stroop test (reading only, low executive function demand) also did not show an exercise effect.

Such a broad, non-specific beneficial effect of exercise on adolescents' cognitive function is in line with the results of several previous studies in adolescents (Budde et al, 2008; McNaughten & Gabbard, 1993; Travlos, 2010; Zervas et al, 1991). Although there are several established theories that postulate differential effects of exercise on specific cognitive functions, the present results do not support this view. Nevertheless, generic improvements in reaction times across different cognitive domains and cognitive load levels could result from increased levels of arousal and increased allocation of attentional resources following exercise. This interpretation would be consistent with the view that a key mediator of the effect of exercise on cognitive function is increased arousal (e.g. Kahnemann, 1973; Lambourne & Tomporowski, 2010), balanced by the negative effects of fatigue for longer, more intense bouts of exercise. Discrepancies between studies could thus result from the specifics of the exercise protocol, because the opposing effects of arousal and fatigue are hypothesised to result in a U-shaped relationship between exercise and cognitive function. The present study also evaluated cognitive function more than 45 minutes after the end of a short bout of exercise, when any potential fatigue effects have probably subsided.

The executive function hypothesis (Churchill et al., 2002; Kramer, Colcombe, McAuley, Scalf & Erickson, 2005), would at first also seem to be consistent with the present results, because attention is considered to be a key component of executive function. However, in that case one would expect significant exercise effects especially on the colour-word incongruent level of the Stroop test (e.g. Hogervorst, Riedel, Jeukendrup and Jolles, 1996), which was not the case here. This may be seen to argue against the executive function hypothesis. However, the lack of an effect could be because the exercise bout may have been insufficiently intense or too brief, or it may not persist for the 45 minutes interval used here, or power may have been too low. Nevertheless, the other cognitive tests did display significant exercise effects. It is possible that reading is not as strongly over-learned and automated in the adolescents tested here as in adults, which could point to one of the reasons that age may modify cognitive effects.

Comparing studies in adults (Barella, Etnier, & Chang, 2010; Chang & Etnier, 2009a, 2009b; Pontifex, Hillman, Fernhall, Thompson, & Valentini, 2009) with the literature on adolescents is thus useful for examining the age effect. In older adults (60 to 90 years old) following 20 min walking, response times on the simple level of the Stroop test were enhanced which is in contrast with the findings of the present study (Barella et al, 2010). However, in line with the present results, on the more complex level of the Stroop test there was no effect of the exercise on response times (Barella et al, 2010). In young (mean age 25 years) and middle aged (35 to 65 years old) participants, resistance exercise was beneficial for response times on the more simple levels of the Stroop test (Chang & Etnier, 2009a, 2009b), and moderate intensity resistance exercise also improved speed on the complex level of the Stroop test (Chang & Etnier, 2009b). Thus, similar to the present results, basic information processing speed was enhanced following exercise in older adults, but there was no specific effect of exercise on executive function as assessed by the complex level of the Stroop test.

In terms of the Sternberg paradigm, in accordance with the findings of the present study, response times were enhanced following aerobic exercise, when compared with both resistance exercise and seated rest in young adults (mean age 20 years) (Pontifex et al, 2009). Thus, the present results and previous literature suggest similar effects of aerobic exercise on adolescents' and adults' performance on the Sternberg paradigm, whereas the effects on performance of the Stroop test appear different between these populations. The differences in findings could be explained by the different exercise protocols used, the timing of the Stroop test relative to exercise and by the age of the participants. The different results in adults and adolescents can at least partly be explained by the continuing maturation of the brain during adolescence, particularly the continuing development of executive function (Giedd et al, 1999), and possibly increased reading proficiency after adolescence.

Possible biological mechanisms explaining the effects of exercise on cognitive function in an adolescent population were investigated in the present study by measuring several brain-relevant blood parameters. Blood glucose, plasma insulin and blood lactate concentrations were better maintained following the mid-morning bout of exercise, whereas they continued to decrease on the resting trial (figures 5, 6 and 7). Glucose is a key metabolic substrate for the brain, thus blood glucose and insulin concentrations may be critical for cognitive function. The pattern of general improvement in response times following exercise, can be partly explained by the higher blood glucose and plasma insulin concentrations following exercise. Several other mechanisms have also been suggested to mediate the effects of exercise on cognitive function, including increased cerebral blood flow, which in combination with higher glucose and insulin concentrations, enhances the delivery of glucose and oxygen to neural tissues and also enhances the clearance of carbon dioxide (Jorgensen et al, 2000).

However, blood glucose and plasma insulin concentrations are not the only potential mechanism to explain the effects of exercise on cognitive function. It has also been suggested that lactate may be oxidised by the brain (Schurr, 2006), though this topic is poorly understood, with some evidence suggesting that lactate is only oxidised by the brain during hypoglycaemia (Maran et al, 1994). However, a recent review indicated that lactate may contribute approximately 7% to cerebral energy requirements at rest, which may increase to 25% during exercise (van Hall, 2010). The findings of the present study suggest that the higher lactate concentrations following exercise (figure 7) were associated with enhanced cognitive performance (e.g. greater speed of working memory) and the effects of lactate on cognitive function are, at the very least, interesting and warrant further investigation.

In summary, the present findings suggest a generic effect of exercise that results in improved response times across several cognitive domains, but no isolated effects on specific or more complex cognitive functions, as effects were seen on all cognitive load levels of the tests. These results extend previous literature by specifically examining an adolescent population and examining the effects of exercise on cognitive function 45 minutes post-exercise, whereas previous studies have tended to focus on the more immediate effects. More work is required in this area, including studies examining the effects of the intensity, duration and mode of exercise on cognitive function in adolescents, and the time for which the beneficial effects of exercise persist. Currently, given the well documented health, social and emotional benefits of break time/recess for young people (Ramstetter et al, 2010) and a general beneficial effect of exercise on the speed of cognitive functions, we conclude that the provision of break time and the opportunity to exercise mid-morning has a beneficial effect on cognitive function in young people.

References

Barella, L.A., Etnier, J.L., & Chang, Y.K. (2010). The immediate and delayed effects of an acute bout of exercise on cognitive performance of healthy older adults. *Journal of Aging and Physical Activity, 18*, 87-98.

Best, J.R. (2010). Effects of physical activity on children's executive function: contributions of experimental research on aerobic exercise. *Developmental Review, 30,* 331-351. doi: 10.1016/j.dr.2010.08.001

Brisswalter, J., Collerdeau, M., & René, A. (2002). Effects of acute physical exercise characteristics on cognitive performance. *Sports Medicine*, *32*, 555-566.

Budde, H., Voelcker-Rehage, C., Pietraβyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters*, *441*, 219-223. doi: 10.1016/j.neulet.2008.06.024

Chang, Y.K., & Etnier, J.L. (2009a). Effects of an acute bout of localized resistance exercise on cognitive performance in middle-aged adults: a randomized controlled trial study. *Psychology of Sport and Exercise, 10,* 19-24. doi: 10.1016/j.psychsport.2008.05.004

Chang, Y.K., & Etnier, J.L. (2009b). Exploring the dose-response relationship between resistance exercise intensity and cognitive function. *Journal of Sport and Exercise Psychology, 31,* 640-656.

Chang, Y.K., Labban, J.D., Gapin, J.I., & Etnier, J.L. (2012). The effects of exercise on cognitive performance: a meta-analysis. *Brain Research, 1453,* 87-101. doi: 10.1016/j.brainres.2012.02.068

Churchill, J.D., Galvez, R., Colcombe, S., Swain, R.A., Kramer, A.F., & Greenhough, W.T. (2002). Exercise, experience and the aging brain. *Neurobiology of Aging, 23*, 941-955.

Cooper, S.B., Bandelow, S., & Nevill, M.E. (2011). Breakfast consumption and cognitive function in adolescent school children. *Physiology & Behavior, 103*, 431-439. doi: 10.1016/j.physbeh.2011.03.018

Cromer, B.A., Tarnowski, K.J., Stein, A.M., Harton, P., & Thornton, D.J. (1990). The school breakfast program and cognition in adolescents. *Developmental and Behavioural Pediatrics*, *11*, 295-300.

Ellemberg, D., & St-Louis-Deschênes, M. (2010). The effect of acute physical exercise on cognitive function during development. *Psychology of Sport and Exercise*, *11*, 122-126. doi: 10.1016.j.psychsport.2009.09.006

Gallotta, M.C., Guidetti, L., Franciosi, E., Emerenziani, G.P., Bonovolontà, V., & Baldari, C. (2012). Effects of varying types of exertion on children's attention capacity. *Medicine and Science in Sports and Exercise, 44,* 550-555. doi: 10.1249/MSS.0b013e318230552

Hillman, C.H., Pontifex, M.B., Raine, L.B., Castelli, D.M., Hall, E.E., & Kramer, A.F. (2009). The effect of acute treadmill walking on cognitive control and academic achievement in preadolescent children. *Neuroscience*, *159*, 1044-1054. doi: 10.1016/j.neuroscience.2009.01.057

Giedd J.N., Blumenthal, J., Jeffries, N.O., Castellanos, F.X., Liu, H., Zijdenbos, A., Paus, T., Evans, A.C., & Rapport, J.L. (1999) Brain development during childhood and adolescence: a longitudinal MRI study. *Nature Neuroscience, 2,* 861-863.

Hillman, C.H., Pontifex, M.B., Raine, L.B., Castelli, D.M., Hall, E.E., & Kramer, A.F. (2009). The effect of acute treadmill walking on cognitive control and academic achievement in preadolescent children. *Neuroscience, 159,* 1044-1054. doi: 10.1016/j.neuroscience.2009.01.057

Hogervorst, E., Riedel, W., Jeukendrup, A. & Jolles, J. (1996). Cognitive Performance after Strenuous Physical Exercise. *Perceptual and Motor Skills 83(2)*, 479-488.

Hogervorst, E., Clifford, A., Stock, J., Xin, X., & Bandelow, S. (2012). Exercise to prevent cognitive decline and Alzheimer's disease: for whom, when, what, and (most importantly) how much? *Journal of Alzheimers Disease & Parkinsonism*, *2*, e117. doi: 10.4172/2161-0460.1000e117

Hoyland, A., Dye, L., & Lawton, C.L. (2009). A systematic review of the effect of breakfast on the cognitive performance of children and adolescents. *Nutrition Research Reviews*, *22*, 220-243. doi: 10.1017/S0954422409990175

Jorgensen, L.G., Nowak, M., Ide, K., & Secher, N.H. (2000). Cerebral blood flow and metabolism. In Saltin, B., Boushel, R., Secher, N., & Mitchell, J. (Eds), *Exercise and circulation in health and disease* (pp 113-236). Champaign: Human Kinetics.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Kanarek, R. (1997). Psychological effects of snacks and altered meal frequency. *British Journal of Nutrition*, *77*, S105-S120.

Kramer, A.F., Colcombe, S.J., McAuley, E., Scalf, P.E., & Erickson, K.I. (2005) Fitness, aging and neurocognitive function. *Neurobiology of Aging*, *26*, 124-127.

Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. *Brain Research*, *1341*, 12-24. doi: 10.1016/j.brainres.2010.03.091

Maran, A., Cranston, I., Lomas, J., MacDonald, I., & Amiel, S.A. (1994). Protection by lactate of cerebral function during hypoglycaemia. *Lancet*, *343*, 16-20.

Maughan, R.J. (1982). A simple, rapid method for the determination of glucose, lactate, pyruvate, alanine, 3-hydroxybutyrate and acetoacetate on a single 20-μl blood sample. *Clinica Chimica Acta*, *122*, 231-240.

McNaughten, D., & Gabbard, C. (1993). Physical exertion and immediate mental performance of sixth-grade children. *Perceptual and Motor Skills*, *77*, 1155-1159.

Pesce, C., Crova, C., Cereatti, L., Casella, R., & Bellucci, M. (2009). Physical activity and mental performance in preadolescents: effects of acute exercise on free-recall memory. *Mental Health and Physical Activity, 2,* 16-22. doi: 10.1016/j.mhpa.2009.02.001

Pontifex, M.B., Hillman, C.H., Fernhall, B., Thompson, K.M., & Vaelntini, T.A. (2009). The effect of acute aerobic and resistance exercise on working memory. *Medicine and Science in Sports and Exercise, 41,* 927-934. doi: 10.1249/MSS.0b013e3181907d69

Querido, J.S., & Sheel, A.W. (2007). Regulation of cerebral blood flow during exercise. *Sports Medicine*, *37*, 765-782.

Ramstetter, C.L., Murray, R., & Garner, A.S. (2010). The crucial role of recess in schools. *Journal of School Health, 80,* 517-526.

Reilly, J.J., & Wilson, D. (2006). ABC of obesity: childhood obesity. *British Medical Journal, 333,* 1207-1210.

Schurr, A. (2006). Lactate: the ultimate cerebral oxidative energy substrate? *Journal of Cerebral Blood Flow & Metabolism*, *26*, 142-152. doi: 10.1038/sj.jcbfm.9600174

Sibley, B.A., & Etnier, J.L. (2003). The relationship between physical activity and cognition in children: a meta-analysis. *Pediatric Exercise Science*, *15*, 243-256.

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

Stroop, J.R. (1935). Stroop Test. *Journal of Experimental Psychology*, *18*, 643-662.

Stroth, S., Kubesch, S., Dieterle, K., Ruschow, M., Heim, R., & Kiefer, M. (2009). Physical fitness, but not acute exercise modulates event-related potential indices for executive control in healthy adolescents. *Brain Research*, *1269,* 114-124. doi: 10.1016/j.brainres.2009.02.073

Thayer, R.E. (1986). Activation-*deactivation* checklist: current overview and structural analysis. *Psychological Report, 58,* 607-614.

Travlos, A.K. (2010). High intensity physical education classes and cognitive performance in eighth-grade students: an applied study. *International Journal of Sport and Exercise Psychology*, *8*, 302-311.

Van Hall, G. (2010). Lactate kinetics in human tissue at rest and during exercise. *Acta Physiologica*, *199*, 499-508. doi: 10.1111/j.1748-1716.2010.02122.x

Van Zomeren, A.H., & Brouwer, W.H. (1992). Assessment of attention. In J.R. Crawford, D.M. Parker, & W.W. McKinlay, (Eds.) *A Hanbook of Neuropsychological Assessment* (pp. 241-266). UK: Lawrence Erlbaum Associates Ltd.

Zervas, Y., Danis, A., & Klissouras, V. (1991). Influence of physical exertion on mental performance with reference to training. *Perceptual and Motor Skills*, *72*, 1215-1221.

Figure 1: Experimental protocol

Figure 2a: Baseline level (trial by session time interaction, $p = 0.131$)

Figure 2b: Complex level (trial by session time interaction, $p < 0.001$)

Figure 2: Response times across the morning on the baseline (**figure 2a**) and complex (**figure 2b**) levels of the visual search test

(trial by session time by test level interaction, $p = 0.009$).

Figure 3a: Baseline level (trial by session time interaction, $p = 0.499$)

Figure 3b: Complex level (trial by session time interaction, $p = 0.046$)

Figure 3: Accuracy across the morning on the baseline (**figure 3a**) and complex (**figure 3b**) levels of the visual search test

(trial by session time by test level interaction, $p = 0.044$).

Figure 4: Response times across the morning on the Sternberg paradigm

(trial by session time interaction, $p = 0.010$).

Figure 5: Blood glucose concentration across the morning. Data are mean ± S.E.M.

(trial by session time interaction, $p<0.001$; * exercise > resting, $p < 0.001$)

Figure 6: Plasma insulin concentrations across the morning. Data are mean ± S.E.M.

(trial by session time interaction, $p = 0.014$; * exercise > resting, $p = 0.024$)

Figure 7: Blood lactate concentrations across the morning. Data are mean ± S.E.M.

(trial by session time interaction, $p = 0.038$; * exercise > resting, $p = 0.005$)