

Effects of continuous and intermittent exercise on executive function in children aged 8-10 years.

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Abstract

Understanding the effects of acute exercise on executive function in prepubescent children may be important for the enhancement of school performance. This study assessed the effect of an acute bout of continuous (CONT) or intermittent (INT), moderate intensity treadmill exercise on executive function in young children. Twenty healthy children (age: 8.8 ± 0.8 y; height: 140 ± 9 cm; body mass: 36 ± 11 kg; boys: $n=9$) performed a graded-exercise test to determine maximal oxygen uptake, and two, 15 minute submaximal bouts of treadmill exercise; protocols were either CONT or INT. During CONT, participants ran at 90% of gas exchange threshold. During INT, participants performed six consecutive, 2.5 minute ‘blocks’ of exercise, which were designed to reflect children’s typical activity patterns, comprising: 45s at a heavy intensity, 33s at a moderate intensity, 10s at a severe intensity, and 62s at a low intensity. Participants performed the Stroop task before- and after (1min_Post, 15min_Post, 30min_Post) the submaximal exercise bouts. Near-infrared spectroscopy (NIRS) measured cerebral perfusion and oxygenation. Regardless of Condition, Stroop performance was improved at 1min_Post compared to Pre (54.9 ± 9.8 cf. 57.9 ± 11 s, respectively, $P < 0.01$) and improvements were maintained until 30min_Post. NIRS (oxyhaemoglobin, total haemoglobin) explained a significant amount of variance in the change in Stroop performance for INT only (49%, $P < 0.05$). An acute bout of exercise, of either an intermittent or continuous nature, improves executive function in children, and effects are maintained for ≤ 30 minutes following exercise cessation. Accordingly, it is recommended that children should engage in physical activity during periods of school recess.

Introduction

There is mounting evidence for the role of acute exercise and physical activity in improving cognitive performance, particularly with young adults or adolescents (Chang, Labban, Gapin, & Etnier, 2012; Diamond & Lee, 2011). However, the relationship between exercise and cognition in prepubescent children is less well-known. Importantly, there is some evidence to suggest that enhancing executive function, in particular, during early development can enhance school performance (Blair & Razza, 2007), can lead to better overall health, as well as personal (Eakin et al., 2004) and socioeconomic (Moffitt et al., 2011) outcomes in adulthood. However, there is still no clear indication of the optimal acute exercise paradigm for enhancing executive function in children (Chang, et al., 2012). Further research is required to elucidate: i) the optimal exercise protocol, ii) the duration of any improvements post-exercise, and iii) to mechanistically link exercise and executive function, in children.

Although exercise intensity has received widespread attention, the influence of exercise protocol, specifically (e.g., continuous versus intermittent), on executive function in young children has not been investigated. This is important as children characteristically exhibit, and are more likely to tolerate, highly intermittent physical activity patterns (Howe, Freedson, Feldman, & Osganian, 2010) – which comprise proportionally more low-moderate intensity exercise periods interspersed with short bouts of high-intensity exercise – particularly during periods of school recess (Lopes, Vasques, Pereira, Maia, & Malina, 2006; Ridgers, Toth, &

Uvacek, 2009). Furthermore, compared to low- or moderate-intensity activity, high-intensity, intermittent [aerobic] training has been shown to be more strongly associated with various positive health outcomes in children (body composition, cardiorespiratory fitness) (Carson et al., 2014; Hay et al., 2012). As such, it is plausible that intermittent exercise of an overall, average moderate intensity, but which is interspersed with a high-intensity component, may be more beneficial for the health and well-being of children than a simple bout of continuous moderate intensity exercise. When implementing acute, intermittent, high and low intensity bouts of exercise (2 x 3 min bouts) within a prolonged bout (~1 h) of moderate intensity exercise with adults, Rattray & Smee (2015) demonstrated significant improvements in response time of a speed match test when compared to a non-exercise control condition. The protocol design of this aforementioned study somewhat reflects the normal patterns of physical activity behaviour of a child, and leads us to speculate that a similar improvement in cognition could be observed with ecologically-designed, intermittent exercise protocols with children. School recess (~15 minutes in duration) provides children with a non-curriculum context to engage in physical activity on a daily basis (Ridgers, et al., 2009) and thus, may offer a window of opportunity for the enhancement of health and school performance, particularly of executive function, should normal patterns of intermittent exercise behaviour be shown to be of benefit.

While a complex issue, it is accepted that acute exercise benefits cognitive performance (Chang, et al., 2012), and a number of mechanisms have been proposed to mediate the positive effects of acute exercise on neurocognitive functions in adults (Verburgh, Konigs, Scherder, & Oosterlaan, 2014). The physiological mechanisms underpinning the relationship between acute exercise and executive function in children however requires greater attention (Jager, Schmidt, Conzelmann, & Roebbers, 2014). It has been suggested that the relationship between exercise

intensity and cognitive performance during exercise is best described as an inverted-U; where cognitive performance is optimal at moderate exercise intensities, but reduced at both low- and high intensities (Ratray & Smee, 2015). This has been attributed to increasing levels of circulating catecholamines and brain-derived neurotrophic factor (BDNF), among others, which may transiently enhance the neural response to a challenging task, possibly through an induced, increased state of arousal (Best, 2010; Verburch, et al., 2014). However, research in this area has proven equivocal (Chmura, Nazar, & Kaciuba-Uścilko, 1994; McMorris, Collard, Corbett, Dicks, & Swain, 2008), not least due to the complications that arise when attempting to compare studies that use differing research designs, cognitive assessments, and sample characteristics. Conversely, the Drive theories posit that high intensity exercise will maximise the effects on cognition, particularly if there is a delay between the exercise session and the cognitive task performance (Chang, et al., 2012).

Acute elevations in mean cerebral blood flow have also been linked to changes in cognitive functioning (Lucas, Ainslie, Murrell, Thomas, Franz, & Cotter, 2012), and it is plausible that moderate intensity exercise may augment executive function as a result of peak oxygenation to the prefrontal lobe (Ando, Yamada, & Kokubu, 2010). Indeed, both children and adults show significant activation in the prefrontal regions of the brain when performing cognitive shifting, inhibitory control and working memory tasks (Moriguchi & Hiraki, 2013). Activities which require intermittent changes in exercise intensity, however, present a more complex situation as proposed physiological changes that likely influence cognition can be short lived (Ratray & Smee, 2015). Nevertheless, near-infrared spectroscopy (NIRS) offers a non-invasive and valid means of assessing prefrontal cortex perfusion and oxygenation, it can be implemented during exercise (Rooks, Thom, McCully, & Dishman, 2010), and presents a

viable option for use with children. Previous research with young adults has shown NIRS to be an effective tool for examining the cognitive effect of an acute bout of low- or moderate-intensity exercise on executive function (Byun et al., 2014; Yanagisawa et al., 2010). It relies on regional differences in cerebral blood flow to delineate regional activity, and in this regard, an increased cortical activation to the prefrontal cortex post-exercise, as monitored by NIRS, has been shown to correspond with improved cognitive performance (Byun, et al., 2014).

The specific timing of cognitive test administration may moderate the effect of acute exercise on cognition. As shown in a recent meta-analysis, when cognitive performance is assessed immediately post-exercise, the greatest positive change has been shown to occur following ‘very light’ to ‘moderate’ intensity exercise (Cohen’s d : 0.12–0.17) (Chang, et al., 2012). However, when assessed following a delay post-exercise, it appears that a prior bout of ‘very hard’ intensity exercise results in the largest effect on cognition (Cohen’s d : 0.20–0.47) (Chang, et al., 2012). In addition, the time delay in assessment post-exercise appears to be particularly important, as the greatest positive effect on cognition has been shown to occur 11–20 min after exercise cessation, with effects subsiding following a longer delay (>20 min) (Chang, et al., 2012). Determination of the temporal change in executive function post-exercise could be of pragmatic importance for the school environment as it may elucidate the optimal exercise paradigm to be encouraged during recess, as well as offer insight into the corresponding optimal timing for presenting children with cognitive tasks (Jarrett et al., 1998; Pellegrini & Bohn, 2005; Ramstetter, Murray, & Garner, 2010).

The purpose of this study was to assess the effect of an acute bout of continuous (CONT) or intermittent (INT), moderate intensity treadmill exercise on executive function in young children. It was hypothesised that i) both CONT and INT exercise would elicit positive

improvements in executive function, but that INT would demonstrate a greater effect than CONT, and ii) **in line with previous research (Chang et al., 2012)**, the reported benefits would be maintained for at least 15 minutes post-exercise.

Methods

Participants

Twenty healthy children (8.8 ± 0.8 y; 140 ± 9 cm; 36 ± 11 kg; boys, $n = 9$) who were asymptomatic of illness and pre-existing injury, and were in the ‘concrete operational stage’ of cognitive development (Piaget, 1999), participated in the study. Based on effect sizes for variables of interest reported in Chang et al. (2012), a minimum sample size of $n = 20$ was calculated to achieve a statistical power of 80% at an alpha of $P < 0.05$. Written child assent and parental/guardian consent were obtained, and research was conducted following the guidelines and policies of the institutional ethics committee.

Procedures

This study employed a randomised cross-over design. Children performed a continuous graded-exercise test (GXT) to maximal functional capacity, followed by two submaximal exercise protocols on a treadmill (True 825, Fitness Technologies, St. Louis, USA), under standard laboratory conditions (temperature: $20.8 \pm 1.2^\circ\text{C}$; humidity: $41.7 \pm 3.2\%$; pressure: 763 ± 3 mmHg). The submaximal protocols comprised a continuous bout of exercise (CONT) and an intermittent bout of exercise (INT), **both of which equated to the ‘moderate intensity exercise domain’**. **These submaximal protocols** were performed in a counterbalanced order, on two different days, separated by a washout period of 48-72 h. The duration of each submaximal

exercise bout was 15 minutes as exercise sessions >11 minutes in duration - which align with periods of school recess – have been shown to elicit the most notable positive changes in executive function (Chang, et al., 2012). The treadmill gradient was set at 1% throughout all exercise protocols (Jones & Doust, 1996). Respiratory variables including oxygen uptake ($\dot{V}O_2$), carbon dioxide ($\dot{V}CO_2$), minute ventilation (\dot{V}_E) and respiratory exchange ratio (RER) were recorded using a breath-by-breath automatic gas exchange system (Sensormedics Corporation, Yorba Linda, CA, USA). Children wore a paediatric wireless chest strap telemetry system to monitor heart rate (Polar Electro T31, Kempele, Finland) and a portable NIRS device (Portalite, Artinis Medical Systems BV, Zetten, The Netherlands) to measure cerebral perfusion and oxygenation. Prior to each exercise test, participants were seated for 10-minutes to allow resting baseline measurement of NIRS, heart rate and respiratory variables. All physiological variables were recorded continuously throughout the exercise protocols. Physiological and speed parameters were concealed from participants.

Children were familiarised with the equipment and testing methodologies, including the cognitive assessment of executive function (Stroop task) both pre- and post the GXT, on the first laboratory visit. The cognitive task was performed prior to- (Pre) and following (1min_Post, 15min_Post, 30min_Post) both submaximal exercise bouts to assess temporal changes in executive function.

Measures

NIRS

Prefrontal cortex perfusion and oxygenation were assessed using a continuous wave NIRS device positioned above the supra orbital ridge of the participant's dominant side. The

device generates near-infrared light at two wavelengths, 760 nanometers (nm) and 850 nm, from three light emitting diodes (inter-optode distances of 30, 35, and 40 mm between the receiver and each of the three diodes). The two wavelengths correspond to the absorption wavelengths of deoxyhaemoglobin (HHb) and oxyhaemoglobin (O₂Hb), respectively. The device measures the intensity of the transmitted and received light, with the absorbed fraction being a measure of the respective haemoglobin concentration. This allows quantification of relative O₂Hb and HHb concentrations, with their sum being equal to total haemoglobin (tHb, perfusion). As such, O₂Hb provides an indication of oxygen delivery, HHb reflects oxygen consumption, which is similar to the information provided by the blood oxygenation level dependent (BOLD) signal when using functional magnetic resonance imaging, and tHb represents total perfusion, which is similar to the information provided by positron emission tomography.

Stroop task

The Stroop task is a classic measure of prefrontal cortex function (Lucas et al., 2012) which has been widely used to assess the effects of acute exercise on executive function (Chang et al., 2012; Hogervorst et al., 2008; Vasques, Moraes, Silveira, Deslandes, & Laks, 2011). In this study, the Stroop interference task was administered as it is more sensitive to executive function than the traditional Stroop word task (Durgin, 2000). Participants completed the Stroop interference task (Xavier Educational Software Ltd., Bangor, Wales), wherein four words ('blue', 'yellow', 'green', 'red') were randomly presented, consecutively, on a computer screen. The colour each word was presented in was either congruent or incongruent with the relevant semantic information (e.g., 'red' presented in the colour red or the colour green,

respectively). Participants were tasked with identifying the colour of each word being presented as quickly as possible, responding by clicking on the respective answer button (blue, yellow, green, red). Each presentation of a word constituted a sequence; each test comprised 32 sequences. The total time to complete the test (completion time), average time per response (reaction time), and number of correct answers (response accuracy) were recorded as measures of performance (Pre, 1min_Post, 15min_Post, 30min_Post).

Exercise Protocols

Continuous maximal graded exercise test (GXT)

A continuous GXT using 1-minute, sequential increments of: 4, 6, 8, 8.5, 9, 9.5 and 10.5 km·h⁻¹, as necessary, was implemented to assess maximal functional capacity (i.e., $\dot{V}O_{2peak}$); as determined by volitional exhaustion. Following a 15 minute passive recovery, a ‘verification test’ (Barker, Williams, Jones, & Armstrong, 2011), wherein children ran at 105% of the peak treadmill speed achieved from the preceding maximal GXT until volitional exhaustion, was used to validate $\dot{V}O_{2peak}$.

The V-slope method was used to analyse the slopes of $\dot{V}O_2$ and $\dot{V}CO_2$ volume curves from the maximal GXT to determine the running speed equivalent with the gaseous exchange threshold (GET) (Beaver, Wasserman, & Whipp, 1986). The running speed equivalent to 40% delta (Δ ; difference between GET and $\dot{V}O_{2peak}$) was subsequently calculated. The running speeds identified at 90% GET (moderate) and 40% delta (heavy) were verified by three independent researchers and were used for the subsequent submaximal exercise bouts (Jones & Poole, 2005).

Continuous submaximal exercise protocol (CONT).

Participants ran continuously for 15 minutes at a running speed equivalent to 90% GET, as ascertained from the maximal GXT (Supplementary Figure 1).

Intermittent submaximal exercise protocol (INT).

This protocol involved six consecutive, 2.5 minute ‘blocks’ of exercise (15 minutes in total). These ‘blocks’ were designed to reflect the typical duration and activity patterns of children as identified during unstructured recess (Lopes, et al., 2006; Ridgers, et al., 2009). Accordingly, each block comprised the following: 45 seconds at a heavy intensity (running speed equivalent to 40 % Δ), 33 seconds at a moderate intensity (running speed equivalent to 90% GET), 10 seconds at a severe intensity (participants’ peak running speed from the maximal GXT), and 62 seconds at a low intensity (self-selected walking pace) (Supplementary Figure 1). **Thus, when these exercise intensities are combined, the average exercise intensity of this protocol equated to the children physiologically working within a ‘moderate intensity exercise domain’ (Jones & Poole, 2005).**

Data analysis

NIRS data (O_2Hb , HHb , tHb) from CONT and INT were filtered by Gaussian smoothing and exported at a sample rate of 2 Hz. NIRS data for each time point (Pre, 1min_Post, 15min_Post, 30min_Post), which are typically measured in micromol/L, were calculated as a proportion of the resting baseline value, to facilitate inter-individual comparisons, and used in the subsequent analyses.

Statistical analysis

Stroop task performance (completion time [s], reaction time [ms], & response accuracy) from the two submaximal exercise bouts were assessed using a series of three-factor repeated-measures ANOVA: Condition (CONT, INT) by Time (Pre, 1min_Post, 15min_Post, 30min_Post) by Session order (CONT followed by INT, INT followed by CONT). Identical analyses were performed to assess changes in O₂Hb, HHb and tHb. Post-hoc analyses using *t*-tests, with Bonferroni adjustment where applicable, were performed as necessary. To assess whether prefrontal cortex perfusion and oxygenation explained a significant amount of variance in the change (Pre vs. 1min_Post) in Stroop task performance (dependent variable: **completion time**), O₂Hb, HHb and tHb (independent variables) were entered in to a multiple regression model. A series of two-factor ANOVA were used to assess the difference in average physiological (HR, $\dot{V}O_2$, \dot{V}_E , RER, energy expenditure), physical (speed), and perceptual (RPE) responses between CONT and INT. All analyses were performed using SPSS version 21, with an alpha of $P < 0.05$ and effect sizes determined as 0.01 (small), 0.06 (medium), and 0.14 (large) using partial eta-squared η^2_p (Cohen, 1992).

Results

Table 1 and 2 summarize the participants' demographic information and peak physiological values from the GXT. The mean $\dot{V}O_2$ at GET and 40% Δ were $40.9 \pm 7.0 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ($66.6 \pm 6.2\% \dot{V}O_{2\text{peak}}$) and $49.4 \pm 7.6 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ($80.4 \pm 4.1\% \dot{V}O_{2\text{peak}}$), respectively. The mean treadmill speeds at 90% GET and 40% Δ were 7.4 ± 0.8 and $8.6 \pm 0.6 \text{ km}\cdot\text{h}^{-1}$, respectively. Average HR, $\dot{V}O_2$, \dot{V}_E , speed and energy expenditure during CONT were significantly higher than during INT (all $P < 0.05$), while RER and RPE were statistically similar (both $P > 0.05$; see Table 3 and Supplementary Table 1).

Stroop task performance: completion time, reaction time and response accuracy

Session order did not influence Stroop task performance across Conditions or Time (all $P > 0.05$). There was no Condition by Time interaction ($P > 0.05$), but significant Condition ($F_{(1, 18)} = 23.50$, $\varepsilon = 1$, $\eta^2_p = 0.566$, $P < 0.001$) and Time ($F_{(3, 54)} = 2.85$, $\varepsilon = 0.758$, $\eta^2_p = 0.137$, $P < 0.05$) main effects were observed for the Stroop task. For the Condition main effect, post-hoc analysis demonstrated that participants completed the Stroop task in a significantly shorter time for INT compared to CONT (53.5 ± 9.6 s cf. 57.7 ± 10.6 s, respectively, $P < 0.01$; Figure 1a). For the Time main effect, Stroop performance was significantly improved at 1min_Post compared to Pre (54.9 ± 9.8 cf. 57.9 ± 11 s, respectively, $P < 0.01$). There were no significant differences in Stroop performance thereafter between consecutive time points (i.e., between 1min_Post & 15min_Post, 15min_Post & 30min_Post; $P > 0.05$). Identical findings were observed for reaction time (Figure 1b). When considering the response accuracy, only a Time main effect was observed ($P < 0.01$; Figure 1c).

NIRS

There was no Condition by Time interaction, nor any Condition main effects for any of the NIRS measures (all $P > 0.05$). Time main effects were observed for O₂Hb ($F_{(3, 57)} = 37.911$, $\varepsilon = 0.752$, $\eta^2_p = .666$; $P < 0.001$), tHb ($F_{(3, 57)} = 29.553$, $\varepsilon = 0.730$, $\eta^2_p = .609$; $P < 0.001$) and HHb ($F_{(3, 57)} = 2.707$, $\varepsilon = 0.893$, $\eta^2_p = .125$; $P = 0.05$). Post-hoc analysis demonstrated a significant increase in O₂Hb and tHb between Pre and 1min_Post, but significant decrements in these variables between 1min_Post and 15min_Post (Figure 2a and 2c, respectively). O₂Hb and tHb remained significantly higher at 15min_Post and 30min_Post compared to Pre (both

$P < 0.001$). For HHb, post-hoc analyses revealed a significant decrement between 1min_Post and 30min_Post ($P < 0.01$; Figure 2b).

Regression analysis

For INT, when all NIRS variables (tHb, O₂Hb, HHb) were entered into the regression analysis, they collectively explained a significant proportion (49.4%) of the variance in Stroop [completion time] performance ($P < .05$). Total perfusion (tHb; main independent variable) significantly accounted for 38.6% of this overall variance ($F_{(1,16)} = 9.44$, $P < .01$; R^2 change = .39; beta [standardized coefficient] = -.62; Standard error = 51.56; beta [unstandardized coefficient] = -158.4), with O₂Hb and HHb explaining a further, non-significant 5.6% and 5.2% of the variance, respectively ($P < .05$). During CONT, none of the NIRS measures (tHb, O₂Hb, HHb) explained a significant amount of the total variance (16%) in overall Stroop performance when all variables were entered into the regression analysis ($P > .05$).

Discussion

This study assessed the effects of an acute bout of CONT and INT treadmill exercise on executive function in young children. In keeping with the study hypothesis, findings demonstrated improvements in executive function immediately (1min_Post) following exercise of a short-duration and these improvements were maintained for up to 30 minutes thereafter, regardless of Condition. Despite no differences in Stroop performance at baseline between Conditions, nor any interaction effect, Stroop performance following INT was, on average, 7.3% better than Stroop performance following CONT (Figure 1). This may reflect the inherent ecological utility of the INT protocol utilised in this study, which was specifically

designed to mimic a child's typical pattern of physical activity during recess. Overall, the findings of this study provide further support for the benefits of acute exercise on executive function in young children.

Although not specifically work-matched (e.g., to a precise energy expenditure; Table 3 & Supplementary Table 1), both CONT and INT protocols were designed to ensure that children would be exercising within a moderate exercise intensity domain, on average. This is in recognition of the moderating effects of exercise intensity on cognition; although, the precise effects and mechanisms involved remains an area of much debate. Nevertheless, by standardising the intensity domain between Conditions, attention could be drawn to the main focus of the study: to assess an ecologically-designed, intermittent bout of exercise against a continuous bout of exercise of equal duration (15 minutes), as from a pragmatic standpoint, this equates to what may happen during a typical period of school recess. In this regard, it is of interest that both acute exercise protocols improved executive function in children when Stroop performance was measured after exercise cessation (1min_Post), although the greatest benefits were observed with INT. According to a meta-analysis by Chang and colleagues (2012), if cognitive performance is measured after a delay (i.e., ≥ 1 min post exercise), a prior bout of hard intensity exercise should be of the greatest benefit. The current study prescribed a moderate intensity exercise domain for both Conditions, yet VO_2 , V_E , and heart rate were all statistically higher during CONT than INT (Table 3 & Supplementary Table 1). In this regard, it is plausible that the greatest effect on executive function may have been observed with CONT; however, this was not the case. Thus, perhaps it is not the exercise intensity per se, but the very nature of the INT protocol (i.e., an average moderate intensity exercise bout, interspersed with 'bursts' of high intensity exercise and low intensity 'recovery' periods) which

has a greater influence on executive function. It is therefore plausible that intermittent protocols may provide an optimal 'format' for eliciting cognitive performance benefit.

Improvements in cognitive performance with exercise have been attributed to an increased state of arousal; an optimal state of which is typically associated with moderate intensity exercise (Best, 2010; Verburgh, et al., 2014). However, in one of few studies to directly compare psychological responses to continuous and high-intensity interval training, Oliveira and colleagues demonstrated that high intensity exercise elicits comparably higher responses on the **Felt Arousal Scale**, and suggest that a high arousal may indicate better vigilance-sustained attention (Oliveira, Slama, Deslandes, Furtado, & Santos, 2013). It is postulated that an exercise-induced arousal state would enhance Stroop performance because executive tasks are highly susceptible to changes in arousal states (Arnsten, 2009). Although it is still debated how this optimal arousal state is reflected at a neurobiological level (Budde et al., 2012), acute elevations in mean cerebral blood flow have been linked to changes in cognitive functioning (Lucas et al., 2012). It is suggested that moderate intensity exercise may augment executive function as a result of peak oxygenation to the prefrontal lobe, as above this intensity cerebral blood flow is reduced (Ando, et al., 2010; Rooks, et al., 2010). In the current study, NIRS demonstrated an increase in oxygen delivery (i.e., O₂Hb) and total perfusion (i.e., tHb) to the prefrontal cortex as a result of exercise (CONT & INT), offering support to the notion that an increase in cerebral blood flow as a result of acute, moderate intensity exercise is linked with enhanced executive function in children. However, as no differences were observed in NIRS measures between Conditions in the present study, and as **subjective ratings of arousal were** not assessed, it is not currently possible to determine the specific relationship

of these aforementioned factors on the findings of this study. It does, however, warrant future consideration.

Improvements in Stroop performance at 1min_Post were maintained for up to 30 minutes following exercise (Figure 1). This is in contrast to the findings of Chang and colleagues' meta-analysis (2012) that suggests that the greatest positive effect on cognition occurs 11-20 min after exercise cessation, with effects subsiding following a longer delay (>20 min). Yet, despite being informative, these aforementioned findings must be viewed cautiously as meta-analytical techniques can mask some effects of moderator variables on key outcomes. Therefore, it is impossible to interpret the findings of Chang et al. (2012) in relation to executive function, per se, or to generalise the findings to a specific-aged paediatric population, as was utilised in the present study. **In this regard, two recent studies (Peiffer, Darby, Fullenkamp and Morgan, 2015; Tsukamoto, et al., 2016) have shown that improvements in cognition can be maintained for a period of 30 minutes post-exercise, in keeping with the findings of the present study. It is likely that our findings are** related to an elevated level of cerebral perfusion, as NIRS demonstrated O₂Hb and tHb to remain statistically elevated from baseline for up to 30 minutes following exercise cessation (Figure 2). This may have practical implications for the school environment as it demonstrates a window of opportunity for presenting children with tasks that challenge executive function following participation in an acute bout of exercise. Nevertheless, it would be pertinent to identify the longevity of the effects of CONT and INT on executive function (e.g., >30 min post-exercise) as this may provide further evidence for the importance of exercise in the school environment for improving the academic performance of young children.

On average, executive function was shown to be better for INT compared to CONT. Given that both Conditions were in a comparable average moderate intensity domain, as reflected by the children's perceptions of exertion (Supplementary Table 1), we can assume that any differences in Stroop performance are related to the inherent differences in exercise intensity profiles between the two protocols; that being that the intermittent protocol included short bouts of low- and high-intensity activity that CONT did not. The positive effects of intermittent exercise in the current study are supported by some of the NIRS findings. In particular, the regression analysis demonstrated that a significant proportion (49.4%) of the change in Stroop performance during INT was accounted for by NIRS markers collectively. Such a finding was not observed however for CONT. **In comparison to CONT, INT requires more complex coordination of motor movements, which has been shown to increase cerebral blood flow to the prefrontal cortex as a result of the increased demand on executive function (Budde, Voelcker-Rehage, Pietraßyk-Kendziorra, Ribeiro, & Tidow, 2008; Manders, 2012; Roland, 1993).** However, when considering that 50.6% of the variance for change in executive function (Stroop performance) remained unexplained according to regression analysis, and as ANOVA showed no differences in the change in NIRS between Conditions, some other mechanism/s must also be contributing to the observed exercise-induced improvements in executive function with INT.

It has been suggested that the exercise-induced up-regulation of neurotransmitters such as dopamine, serotonin, norepinephrine and endorphine (Barenberg, 2012; Best, 2010; Meeusen, Watson, Hasegawa, Roelands, & Piacentini, 2006), as well as BDNF (**Saucedo-Marquez, Vanaudenaerde, Troosters & Wenderoth, 2015**), may play a crucial role in improving executive function (Barenberg, 2012; Robbins & Arnsten, 2009). **Saucedo-Marquez et al.**

(2015) have recently shown greater elevations in serum BDNF during high-intensity intermittent exercise when compared to continuous high-intensity exercise. In this regard, short periods of intense exercise, as were utilised during INT in the current study, have been shown to directly improve learning, up to 20% faster than continuous, moderate intensity exercise, in conjunction with elevated levels of peripheral catecholamines and BDNF (Winter et al., 2007). From an exercise psychology perspective, although strenuous exercise may result in greater depletion of self-control, potentially negatively impacting on executive functions, this relationship can be moderated by the effects of mood; an increase in which, as a result of acute exercise, may lead to more positive effects on subsequent tasks of executive function (Audiffren & Andre, 2014). In this regard, it is plausible that differences in the children's mood as a result of the two Conditions may have impacted on their subsequent Stroop performance. As mood state can be linked to the level of enjoyment of an exercise task, it is pertinent that past research has shown that children report high levels of enjoyment when undertaking high-intensity, playground games-based activities (Lambrick, Westrupp, Kaufmann, Stoner & Faulkner, 2015). Nevertheless, as these aforementioned physiological and psychological factors were not measured in the current study, such relationships cannot be determined at this time, for this population. Future research should therefore continue to examine a variety of exercise protocols and the relationships between underlying physiological (cerebral blood flow and oxygenation, neurotransmitters) and psychological (arousal, mood state) mechanisms to determine the optimal circumstances for eliciting improved executive function in young children.

The pragmatic design of this study aids in determining whether normal patterns of physical activity behaviour during recess may positively influence subsequent cognitive

performance in the classroom setting, yet, it is pertinent to recognise the potential limitations of the study design. Firstly, the research was conducted in a laboratory rather than a real school environment which, despite allowing control over many extraneous variables, limits the ecological utility of the findings. Secondly, the two exercise protocols were matched according to the duration of the exercise bout (15 minutes) in order to provide a standardised comparison to a typical period of school recess. However, this inevitably meant that the two protocols were not specifically work-matched (although, both were considered to be within an average moderate intensity domain) and thus, the findings may have been influenced by differences in energy expenditure between the two conditions. Future research should aim to identify the effects of differing acute exercise protocols when not matched for duration.

In conclusion, the present study demonstrates that an acute bout (15 minutes duration) of exercise, of either an intermittent or continuous nature, elicits significant improvements in executive function in young children, and that these effects are maintained for up to 30 minutes following exercise cessation. Accordingly, it is recommended that children should engage in physical activity during periods of school recess. Although both continuous and intermittent exercise bouts would likely promote subsequent academic performance, specifically tasks involving executive function, intermittent exercise may prove **more** beneficial. Although the findings of the current study provide tentative evidence that increases in cerebral blood flow and oxygenation to the prefrontal cortex are associated with improvements in executive function, the exact nature of such a relationship, as well as other potential underlying mechanisms, warrants further investigation in this population.

References:

- Ando, S., Yamada, Y., & Kokubu, M. (2010). Reaction time to peripheral visual stimuli during exercise under hypoxia. *Journal of Applied Physiology*, (1985), 108(5), 1210-1216. doi: 10.1152/jappphysiol.01115.2009
- Arnsten, A. F. (2009). Toward a new understanding of attention-deficit hyperactivity disorder pathophysiology: an important role for prefrontal cortex dysfunction. *CNS Drugs*, 23 Suppl 1, 33-41. doi: 10.2165/00023210-200923000-00005
- Audiffren, M., & Andre, N. (2015). The strength model of self-control revisited: linking acute and chronic effects of exercise on executive functions. *Journal of Sport and Health Science*, 4, 30e46.
- Barenberg, J. (2012). Executive Functions in Learning Processes: Do They Benefit from Physical Activity. *Educational Research Review*, 6(3), 208-222.

- Barker, A. R., Williams, C. A., Jones, A. M., & Armstrong, N. (2011). Establishing maximal oxygen uptake in young people during a ramp cycle test to exhaustion. *British Journal of Sports Medicine* 45(6), 498-503. doi: 10.1136/bjism.2009.063180
- Beaver, W. L., Wasserman, K., & Whipp, B. J. (1986). A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology*, 60(6), 2020-2027.
- Best, J. R. (2010). Effects of Physical Activity on Children's Executive Function: Contributions of Experimental Research on Aerobic Exercise. *Developmental Review* 30(4), 331-351.
- Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development*, 78(2), 647-663. doi: 10.1111/j.1467-8624.2007.01019.x
- Budde, H., Brunelli, A., Machado, S., Velasques, B., Ribeiro, P., Arias-Carrion, O., & Voelcker-Rehage, C. (2012). Intermittent maximal exercise improves attentional performance only in physically active students. *Archives of Medical Research*, 43(2), 125-131. doi: 10.1016/j.arcmed.2012.02.005
- Budde, H., Voelcker-Rehage, C., Pietraszyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters*, 441, 219-223.
- Byun, K., Hyodo, K., Suwabe, K., Kujach, S., Kato, M., & Soya, H. (2014). Possible influences of exercise-intensity-dependent increases in non-cortical hemodynamic variables on NIRS-based neuroimaging analysis during cognitive tasks: Technical note. *Journal of Exercise Nutrition & Biochemistry*, 18(4), 327-332. doi: 10.5717/jenb.2014.18.4.327

- Carson, V., Rinaldi, R. L., Torrance, B., Maximova, K., Ball, G. D., Majumdar, S. R., . . . McGavock, J. (2014). Vigorous physical activity and longitudinal associations with cardiometabolic risk factors in youth. *International Journal of Obesity*, 38(1), 16-21. doi: 10.1038/ijo.2013.135
- Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Research*, 1453, 87-101. doi: 10.1016/j.brainres.2012.02.068
- Chmura, J., Nazar, K., & Kaciuba-Uściłko, H. (1994). Choice Reaction Time During Graded Exercise in Relation to Blood Lactate and Plasma Catecholamine Thresholds. *International Journal of Sports Medicine*, 15(04), 172-176. doi: 10.1055/s-2007-1021042
- Cohen, J. (1992). A power primer. *Psychological Bulletin*, 112(1), 155-159.
- Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science*, 333(6045), 959-964. doi: 10.1126/science.1204529
- Durgin, F. H. (2000). The reverse Stroop effect. *Psychonomic Bulletin & Review*, 7(1), 121-125.
- Eakin, L., Minde, K., Hechtman, L., Ochs, E., Krane, E., Bouffard, R., . . . Looper, K. (2004). The marital and family functioning of adults with ADHD and their spouses. *Journal of Attention Disorders*, 8(1), 1-10.
- Hay, J., Maximova, K., Durksen, A., Carson, V., Rinaldi, R. L., Torrance, B., . . . McGavock, J. (2012). Physical activity intensity and cardiometabolic risk in youth. *Archives of Pediatrics & Adolescent Medicine*, 166(11), 1022-1029. doi: 10.1001/archpediatrics.2012.1028

- Hogervorst, E., Bandelow, S., Schmitt, J., Jentjens, R., Oliveira, M., Allgrove, J., Carter, T., & Gleeson, M. (2008). Caffeine improves physical and cognitive performance during exhaustive exercise. *Medicine and Science in Sports and Exercise*, 40, 1841-1851. doi: 10.1249/MSS.0b013e31817bb8b7
- Howe, C. A., Freedson, P. S., Feldman, H. A., & Osganian, S. K. (2010). Energy expenditure and enjoyment of common children's games in a simulated free-play environment. *The Journal of Pediatrics*, 157(6), 936-942.e931-932. doi: 10.1016/j.jpeds.2010.06.041
- Jager, K., Schmidt, M., Conzelmann, A., & Roebers, C. M. (2014). Cognitive and physiological effects of an acute physical activity intervention in elementary school children. *Frontiers in Psychology*, 5, 1473. doi: 10.3389/fpsyg.2014.01473
- Jarrett, O. S., Maxwell, D. M., Dickerson, C., Hoge, P., Davies, G., & Yetley, A. (1998). Impact of Recess on Classroom Behavior: Group Effects and Individual Differences. *The Journal of Educational Research*, 92(2), 121-126. doi: 10.1080/00220679809597584
- Jones, A. M., & Doust, J. H. (1996). A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *Journal of Sports Sciences*, 14(4), 321-327. doi: 10.1080/02640419608727717
- Jones, A. M., & Poole, D. C. (2005). Oxygen uptake dynamics: from muscle to mouth--an introduction to the symposium. *Medicine and Science in Sports and Exercise*, 37(9), 1542-1550.
- Lambrick, D., Westrupp, N., Kaufmann, S., Stoner, L., & Faulkner, J. (2016). The effectiveness of a high-intensity games intervention on improving indices of health in young children. *Journal of Sports Sciences*, 34(3), 190-198. doi: 10.1080/02640414.2015.1048521.

- Lopes, V., Vasques, M., Pereira, M., Maia, J., & Malina, R. (2006). Physical Activity Patterns During School Recess: A Study in Children 6 to 10 Years Old. *International Electronic Journal of Health Education*, 9, 192-201.
- Lucas, S. J., Ainslie, P. N., Murrell, C. J., Thomas, K. N., Franz, E. A., & Cotter, J. D. (2012). Effect of age on exercise-induced alterations in cognitive executive function: relationship to cerebral perfusion. *Experimental Gerontology*, 47, 541-551. doi: 10.1016/j.exger.2011.12.002.
- Manders, J. (2012). *The Effect of Physical Activity on Executive Functioning in Children: A review*. Tilburg: Tilburg University.
- McMorris, T., Collard, K., Corbett, J., Dicks, M., & Swain, J. P. (2008). A test of the catecholamines hypothesis for an acute exercise–cognition interaction. *Pharmacology Biochemistry and Behavior*, 89(1), 106-115. doi: <http://dx.doi.org/10.1016/j.pbb.2007.11.007>
- Meeusen, R., Watson, P., Hasegawa, H., Roelands, B., & Piacentini, M. F. (2006). Central fatigue: the serotonin hypothesis and beyond. *Sports Medicine*, 36(10), 881-909.
- Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., . . . Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences of the United States of America*, 108(7), 2693-2698. doi: 10.1073/pnas.1010076108
- Moriguchi, Y., & Hiraki, K. (2013). Prefrontal cortex and executive function in young children: a review of NIRS studies. *Frontiers in Human Neuroscience*, 7, 867. doi: 10.3389/fnhum.2013.00867

- Oliveira, B. R., Slama, F. A., Deslandes, A. C., Furtado, E. S., & Santos, T. M. (2013). Continuous and high-intensity interval training: which promotes higher pleasure? *PLoS One*, 8(11), e79965. doi: 10.1371/journal.pone.0079965
- Peiffer, R., Darby, L. A., Fullenkamp, A., & Morgan, A. L. (2015). Effects of acute aerobic exercise on executive function in older women. *Journal of Sports Science and Medicine*, 14(3), 574-583.
- Pellegrini, A. D., & Bohn, C. M. (2005). The Role of Recess in Children's Cognitive Performance and School Adjustment. *Educational Researcher*, 34(1), 13-19. doi: 10.3102/0013189x034001013
- Piaget, J. (1999). The stages of the intellectual development of the child. In A. Slater, Muir D (Ed.), *The Blackwell Reader in Developmental Psychology* (pp. 35-42). Oxford: Blackwell Publishing.
- Ramstetter, C. L., Murray, R., & Garner, A. S. (2010). The crucial role of recess in schools. *The Journal of School Health*, 80(11), 517-526. doi: 10.1111/j.1746-1561.2010.00537.x
- Rattray, B., & Smee, D. J. (2015). The effect of high and low exercise intensity periods on a simple memory recognition test. *Journal of Sport and Health Science*. doi: 10.1016/j.jshs.2015.01.005
- Ridgers, N. D., Toth, M., & Uvacsek, M. (2009). Physical activity levels of Hungarian children during school recess. *Preventive Medicine*, 49(5), 410-412. doi: 10.1016/j.ypmed.2009.08.008

- Robbins, T., & Arnsten, A. (2009). The neuropsychopharmacology of fronto-executive function: Monoaminergic modulation. *The Annual Review of Neuroscience*, *32*, 267–287.
- Roland, P. E. (1993). *Brain activation*. New York, NY, US: Wiley-Liss.
- Rooks, C. R., Thom, N. J., McCully, K. K., & Dishman, R. K. (2010). Effects of incremental exercise on cerebral oxygenation measured by near-infrared spectroscopy: a systematic review. *Progress in Neurobiology*, *92*(2), 134-150. doi: 10.1016/j.pneurobio.2010.06.002
- Saucedo-Marquez, C. M., Vanaudenaerde, B., Troosters, T., & Wenderoth, N. (2015). High-intensity interval training evokes larger serum BDNF levels compared with intense continuous exercise. *Journal of Applied Physiology*, *119*(12), 1363-1373. doi: 10.1152/jappphysiol.00126.2015.
- Tsukamoto, H., Suga, T., Takenaka, S., Tanaka, D., Takeuchi, T., Hamaoka, T., . . . Hashimoto, T. (2016). Greater impact of acute high-intensity interval exercise on post-exercise executive function compared to moderate-intensity continuous exercise. *Physiology and Behaviour*, *155*, 224-230. doi: 10.1016/j.physbeh.2015.12.021
- Vasques, P. E., Moraes, H., Silveira, H., Deslandes, A. C., & Laks, J. (2011). Acute exercise improves cognition in the depressed elderly: the effect of dual-tasks. *Clinics*, *66*, 1553-1557.
- Verburgh, L., Konigs, M., Scherder, E. J., & Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: a meta-analysis. *British Journal of Sports Medicine*, *48*(12), 973-379. doi: 10.1136/bjsports-2012-091441

Winter, B., Breitenstein, C., Mooren, F. C., Voelker, K., Fobker, M., Lechtermann, A., . . .

Knecht, S. (2007). High impact running improves learning. *Neurobiology of Learning and Memory*, 87(4), 597-609. doi: 10.1016/j.nlm.2006.11.003

Yanagisawa, H., Dan, I., Tsuzuki, D., Kato, M., Okamoto, M., Kyutoku, Y., & Soya, H. (2010).

Acute moderate exercise elicits increased dorsolateral prefrontal activation and improves cognitive performance with Stroop test. *Neuroimage*, 50(4), 1702-1710. doi:

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Figure Legends:

Figure 1. Mean (\pm SD) Stroop test completion time (s, 1a) reaction time (ms, 1b), and response accuracy (n, 1c), at each assessment time point for CONT and INT.

* Significant difference between Time points ($P < 0.01$)

Significant difference between Conditions ($P < 0.01$)

Figure 2. Mean (\pm SD) percentage change for O₂Hb (2a), HHb (2b) and tHb (2c) for CONT and INT, across Time

*Significant difference between Time points ($P < 0.05$)