# EXECUTIVE FUNCTION PERFORMANCE FOLLOWING EXPOSURE TO CARDIOVASCULAR EXERCISE AT DIFFERENT INTENSITIES

# EXECUTIVE FUNCTION PERFORMANCE FOLLOWING EXPOSURE TO CARDIOVASCULAR EXERCISE AT DIFFERENT INTENSITIES

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## ABSTRACT

Although there is an abundance of research investigating the effects of exercise on cognitive function, few studies have investigated acute effects of exercise on performance of tasks involving executive function. Furthermore, the effects of different exercise intensities on multiple tests of executive function have received little attention. The purpose of this study was to examine the acute effects of 20-minutes of stationary cycling exercise at varying exercise intensities on executive function performance and to determine these acute effects immediately following exercise as well as after 10 and 30-minute delays following exercise. University students ($N$ = 88) completed baseline measures of executive function (stop-signal task [SST] and Stroop task [ST]) and a graded cardiovascular exercise test on Visit 1. On Visit 2, participants were stratified by gender and fitness level and randomized to one of four conditions: high-intensity interval training (HIT), high, moderate or low-intensity steady-state exercise performed on a cycle ergometer. The ST and SST were performed immediately following exercise and again at 10- and 30-minutes post-exercise.

Immediately following exercise, ST response times were significantly different ($p < .05$), demonstrating faster response times for the high and moderate intensity exercise ($p < .05$), while improvements in SST response inhibition were revealed for the HIT ($p < .01$) condition. At 10-minutes post-exercise, moderate and low-intensity conditions revealed improvements in ST response times ($p < .05$), with enhanced SST response inhibition evident in the HIT, moderate and low-intensity conditions ($p < .05$). At 30-minutes post-exercise, ST response times continued to show improvements from baseline for the moderate and low-intensity conditions ($p < .05$), while SST response inhibition trended back towards baseline levels ($p > .05$).

The present outcomes demonstrate beneficial effects of exercise, regardless of intensity, for up to 38 minutes post-exercise. Future research should focus on mechanisms that would account for these effects and factors that support enhanced executive function performance with exercise training.

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| | |
|---|---|
| ANOVA | analysis of variance |
| BDNF | brain-derived neurotrophic factor |
| GXT | graded exercise test |
| HIT | high-intensity interval training |
| HR | heart rate |
| $HR_{MAX}$ | maximum heart rate |
| ms | millisecond |
| RPE | ratings of perceived exertion |
| min | minute |
| PAR-Q | Physical Activity Readiness Questionnaire |
| RPE | ratings of perceived exertion |
| RT | response time |
| sec | seconds |
| SPSS | Statistical Package for the Social Sciences |
| SSRT | stop-signal response time |
| W | watts |
| $W_{max}$ | maximum watts |

## DECLARATION OF ACADEMIC ACHIEVEMENT

**D. M. Y. Brown's role:**

- Author of ethics application at McMaster University
- Created study design and measure selection
- Responsible for participant recruitment
- Lead investigator responsible for preparation of lab settings, equipment and materials
- Responsible for data collection, input, analysis and interpretation
- Supervised volunteers who assisted with data collection

**Role of co-authors:**

- SB assisted DMYB with study design and measurement selection
- SB and JH assisted DMYB with measurement selection
- JH programmed modified computerized Stroop task
- SB obtained study funding
- SB assisted DMYB with obtaining ethics approval at McMaster University
- SB assisted DMYB with interpretation of the data

# INTRODUCTION

On a daily basis, humans rely on several different cognitive processes such as simple reactions to environmental stimuli as well as executive functions. These processes serve a wide range of roles for interaction within our environment including planning and executing actions, remembering past events and how to do perform daily tasks, and delaying short-term gratification in order to achieve long-term goals. How much exercise we do as well as physical fitness has been linked to a number of cognitive processes (Colcombe & Kramer, 2003; Hillman, Erikson, & Kramer, 2008). Accordingly, the effects of exercise on cognitive performance have received a great deal of attention in the past two decades as researchers have attempted to understand the acute (i.e., short term), chronic (i.e., long term effects from training), developmental, aging and lifestyle factors of exercise that influence cognitive functioning (Hillman et al., 2008).

## Exercise and Cognitive Function

A review of the research on the effects of exercise on cognitive function shows a number of distinct areas that have emerged. One important distinction in the literature is in regards to the acute and chronic effects of exercise. Although similar tests of cognitive function and exercise are used, the nature of the research questions addressed in these two areas differ substantially. Studies of the acute effects of exercise on cognition involve the performance of a single bout of exercise, which elicits transient behavioural, physiological, and psychological changes that may occur during exercise or last minutes to hours following exercise (McMorris, Tomporowski, & Audriffen, 2009). These changes modulate the activity of neural networks that produce changes in our cognitive abilities and mental states (McMorris et al., 2009). On the other hand, studies on the chronic effects of exercise on cognitive function are characterized by the performance of multiple bouts of exercise over time and assessing changes in behavioural, physiological, and psychological variables over time or from one point in time to another (e.g., pre-exercise training to post-exercise training). Research on the chronic effects of exercise on cognition focuses on lasting structural changes in the brain including angiogenesis (e.g., Swain et al., 2003), synaptogenesis (e.g., Chu & Jones, 2000) or neurogenesis (e.g., van Praag et al., 1999). The effects of chronic exercise on cognitive function may be seen after a few weeks of training and can be maintained several weeks following termination of an exercise program (McMorris et al., 2009).

Results of recent meta-analyses have indicated that exercise has a small positive effect on cognitive functioning for acute exercise ($g$ = 0.17) (McMorris & Hale, 2012) and a medium positive effect for chronic exercise ($d$ = 0.48) (Colcombe & Kramer, 2003). Although effects of chronic exercise on cognitive performance are of considerable interest in the exercise-cognition literature, for the purpose of the current study, the focus is on the effects of acute exercise protocols on cognitive performance. The acute effects of exercise on cognitive function are important to understand for several reasons. For instance, on a daily basis, we encounter situations that require the utilization of decision-making processes during or following exposure to a stressor. In the case of the acute exercise – cognitive performance relationship, the stressor is exercise or physical activity. Therefore, it is important that we understand the parameters surrounding exercise or the mode and intensity of physical activity to predict how people might react during and following exposure to exercise, whether cognitive performance may be implicated for academic, sport or workplace performance purposes.

**Acute Effects of Exercise on Cognitive Function**

Within the literature examining the acute effects of exercise on cognition, cognitive performance has been assessed during exercise, immediately following exercise, and during the post-exercise recovery period. Narrative reviews of the literature have observed that studies have produced mixed results (e.g., Brisswalter, Collardeau, & René, 2002; Fox, 1999; McMorris & Graydon, 2000; Tomporowski, 2003); however, recent meta-analyses indicate a range of effect sizes from small positive effects (Chang et al., 2012) to large positive effects (McMorris & Hale, 2012) depending on the type and timing of cognitive assessment. When examining effect sizes, both Cohen's *d* and Hedge's *g* can be interpreted using Cohen's (1992) convention table (McGrath & Meyer 2006). It must be noted that these effect size estimators differ, as Cohen's *d* uses the pooled sample standard deviation, where Hedge's *g* utilizes an adjustment to remove the sample size bias of Cohen's *d* (Rosenthal, 1994). Thus, small effect sizes are in the range of .20, medium effects are .50, and large effects are .80 or greater for both Hedge's *g* and Cohen's *d*.

A recent meta-analysis by Chang et al. (2012) found effect sizes of $d$ = 0.10, $d$ = 0.11, and $d$ = 0.10 for acute effects during exercise, immediately following exercise, and after a delay following exercise, respectively. McMorris and Hale's (2012) meta-analysis reported an effect size of $g$ = -0.08 for cognitive performance during exercise and an effect size of $g$ = 0.17 following exercise, demonstrating a facilitative effect of exercise on cognitive performance when assessed following cessation of an acute bout of exercise. In stark contrast to these findings, McMorris and Hale (2012) report a large effect size ($g$ = 0.77) for executive function performance, yet this effect was irrespective of the timing of assessment. These effect sizes serve to illustrate the range of effects that have been reported in the literature to date and clearly there are several important factors to consider when assessing the exercise - cognition relationship.

Among the acute effects that deserve specific attention are those that are seen when cognitive performance is assessed during exercise and following exercise. According to the transient hypofrontality hypothesis (Dietrich, 2003; Dietrich, 2006; Dietrich & Audriffen, 2011), performing exercise requires significant neural and metabolic resources that may compete with performance of cognitive tasks during exercise. However, upon termination of exercise, the cognitive demands associated with movement are removed and different patterns of cognitive performance may be observed. In the current study, the focus is on cognitive function immediately following and during a brief recovery period following exposure to an acute bout of exercise.

Studies examining the acute effects of exercise on cognitive performance immediately following and during post-exercise recovery have also provided mixed results (e.g., Del Giorno, Hall, O'Leary, Bixby, & Miller, 2010; Joyce, Graydon, McMorris, & Davranche, 2009). However, as previously mentioned, recent meta-analyses have indicated that exercise has a positive effect on cognitive performance immediately after exercise ($d$ = 0.11) as well as after a delay following exercise ($d$ = 0.10) (Chang et al., 2012).

Although the overall results point towards a small positive effect of exercise on cognitive performance, there are several additional moderating factors that must be taken into account when interpreting the exercise-cognitive performance relationship. Major factors that influence the magnitude of this effect include the characteristics of the exercise stimulus, which can include the mode (e.g., running, cycling), as well as the intensity and duration of the exercise. However, the existing meta-analyses group effect sizes together to assess these moderators such that they are representative of the overall effect ignoring variations in other factors that may also be influential moderators. For example, according to Chang et al.'s (2012) meta-analysis, when assessed immediately following exercise, small positive effects are evident at very light ($d$ = 0.15), light ($d$ = 0.17), and moderate intensities ($d$ = 0.12), whereas effects are null for high intensity exercise ($d$ = 0.00) and drift towards small negative effects for very high ($d$ = -0.16) and maximal intensity exercise ($d$ = -0.04). These particular results suggest that exercising at high intensity levels or to exhaustion or task failure results in impaired cognitive performance. However, it is not clear whether the size of the effects might differ according to the mode of exercise or the type of cognitive tests being performed.

The size of the effect of exercise on cognitive performance is also moderated by the cognitive processes required by the cognitive tests performed. Current meta-analyses make a distinction between cognitive tests that involve executive functions and those that involve sensorimotor processes. Executive functions are employed in a supervisory role in cognitive processing, using higher order cognitive processes for organization and execution of complex thoughts and behaviours (Alvarez & Emory, 2006). Executive functions are represented by indices of executive processes including working memory, task switching, response inhibition, scheduling and planning (Colcombe & Kramer, 2003; Miyake et al., 2000). These functions require conscious awareness (Rogers & Monsell, 1995) and are responsible for perception, memory and action (Meyer & Kieras, 1997; Norman & Shallice, 1986). Multiple measures of executive functioning are available and include tests such as the Stroop task, Erikson Flanker Task, go/no-go task, and stop-signal task. According to McMorris and Hale's (2012) results, the acute effect of exercise on executive function test performance is $g$ = 0.77. These results demonstrate the facilitative effect exercise has on cognition, moreover, the greatest effects may be revealed for cognitive performance when only including assessments of executive function. However, one shortcoming of McMorris and Hale's study is that executive function at specific time points (i.e., immediately following exercise, after short delay, after longer delays) was not assessed. Furthermore, they did not examine varying effect sizes due to intensity and duration of the exercise performed. Thus, it is not clear whether the size of the effect of exercise on executive function performance may vary depending on the mode, intensity, timing of assessment, or duration of the exercise performed.

In contrast to executive functions, sensorimotor processes involve sensory, perceptual, decisional and motor processes (Sanders, 1983). These are automatic, unconscious processes that serve to function in a reactive way as we navigate our environment. Measures of sensorimotor processes include tests of reaction time (e.g., simple reaction time, choice reaction time) and information processing (e.g., Stroop Colour or Stroop Word Task, Visual Search Task). According to McMorris & Hale

(2012), the acute effect of exercise on sensorimotor processes is $g = 0.31$. However, there are no meta-analytic results that would allow insight into whether sensorimotor processing is differentially affected by acute exercise at different modes, durations, or intensities.

Executive functions and sensorimotor processes are responsible for different roles in cognitive functioning (McMorris et al., 2009). Executive functions are of interest because we rely on higher-level planning, inhibition, and decision-making processes consistently throughout the day in order to navigate our environment. As humans, our lives are dependent on executive function performance in a multitude of settings, and exercise may be a key factor in optimizing performance in key areas of cognitive functioning. Moving forward in the introduction, attention will be on research involving executive function tasks.

To update and summarize, recent meta-analyses (e.g., Chang et al., 2012; McMorris & Hale, 2012) have attempted to both consolidate and tease apart factors that may provide greater insight into the complexities of the acute effects of exercise on cognitive performance. However, those reviews provide no clear evidence directly related to the acute effects of exercise on executive function following exposure to different doses of exercise or at different time points following exercise. To address this shortcoming in the literature, I have undertaken a quantitative summary of the studies examining executive function immediately following exercise (see Table 1) as well as a summary of studies examining executive function after a delay following exercise (see Table 2). The remainder of this chapter will present a summary of the existing literature examining acute exercise and executive function as well as theoretical perspectives that have been applied to understanding these effects. In so doing, I will highlight that although past research has investigated acute effects of varying intensities of exercise on executive function, there are gaps in the literature that are necessary to address.

**Acute Effects of Exercise on Executive Function Immediately after Exercise**

As mentioned previously, two factors that have been found to moderate the exercise – cognitive performance relationship are exercise intensity and the timing of when cognitive performance tasks are assessed. However, to date, there has not been a meta-analysis of studies examining the effects of varying intensities of exercise on executive function. Accordingly, I have prepared a review of existing studies examining executive function immediately and after a delay following exercise to highlight the overarching trends that exist. As illustrated in Table 1, sixteen studies have investigated the acute effects of exercise on executive function immediately after exercise. As not all studies provided sufficient information to derive a quantitative effect size (e.g., Cohen's *d*), the studies are organized in terms of the direction of the observed effects according to the mode, intensity, and duration of the exercise performed as well as the test(s) of executive function assessed. Studies reporting significant ($p < .05$) positive effects were coded as positive (+), effects that were not significant ($p > .05$) were coded as null (0), and effects that were significant ($p < .05$) and negative were coded as (-).

Results from previous studies that examine only executive function in response to low-intensity exercise are limited, as only two studies have been carried out, with null effects observed for all tests. Eighteen effects were derived from 13 studies examining moderate-intensity exercise. Those findings are divided, as there are 8 positive and 10 null effects. Six studies examining high-intensity exercise provide 9 effects, with 4, 2, and 2 effects supporting positive, null and negative effects, respectively. When assessing maximal-intensity exercise until exhaustion, one study provided a null effect. Overall, these results suggest null effects for low and maximal-intensity exercise, whereas moderate and high intensity exercise appears to facilitate executive function. Although determination of an overall effect size was not the purpose of this analysis, some of the effect sizes that could be ascertained from the studies include: Coles and Tomporowski (2008), who report a large effect size ($\eta^2 = 0.54$) and Del Giorno et al. (2010) who reported a medium effect size ($d = 0.54$) for moderate-intensity exercise. A recent study by Alves et al. (2014) also reported a medium effect size ($d = 0.53$) for high-intensity interval training (HIT). Taken together, these results show moderate and high-intensity exercise may provide a medium to large effect on executive function, which is consistent with the large effect size ($g = 0.77$) reported by McMorris and Hale (2012) for exercise on executive function in contrast to the small positive effect ($d = 0.19$) reported by Chang et al. (2012) when examining executive function immediately after exercise.

Table 1

*Studies Examining Executive Function Immediately Following Exercise*

| Study | Population | Exercise Mode, Intensity and Duration | | | Executive Function Test | Direction of Effect |
|---|---|---|---|---|---|---|
| | | Mode | Intensity | Duration (minutes) | | |
| Alves et al. (2014) | Middle-aged Adults ($M_{AGE}$ = 53.7) | Cycling | High-Intensity Intervals (10x1 protocol) | 20 | Digit Span Backward Test | 0 |
| | | | | | Stroop Colour-Word Task | + |
| Coles & Tomporowski (2008) | Young Adults ( $M_{AGE}$ = 22.2) | Cycling | Moderate (60%$VO_2$max) | 40 | Set-shifting task | 0 |
| | | | | | Brown-Peterson task | 0 |
| | | | | | Free recall task | + |
| Del Giorno et al. (2010) | Young Adults ( $M_{AGE}$ = 20.2) | Cycling | Moderate ($V_{TH}$ - 20%) | 20 | WCST | + |
| | | | | | CPT | + |
| | | | High ($V_{TH}$ +10%) | | WCST | - |
| | | | | | CPT | - |
| Ferris et al. (2007) | Young Adults (Mage = 25.4) | Cycling | Moderate ($V_{TH}$ - 10) | 30 | Stroop Colour-Word Task | 0 |
| | | | High ($V_{TH}$ +20) | | | + |
| | | | GXT | Exhaustion | | 0 |
| Griffin et al. (2011) | Young Male Adults ($M_{AGE}$ = 22.0) | Cycling | GXT | Exhaustion | Face-name task | + |
| | | | | | Stroop Colour-Word task | 0 |
| Heckler & Croce (1992) | Female Adults ($M_{AGE}$ = 28.2) | Treadmill | Moderate (~55% $VO_2$max) | 20 | Mental Arithmetic Problem Solving | 0 |
| | | | | 40 | | 0 |
| Hogervorst et al. (1996) | Young Male Adults | Cycling | High (75% MAP) | 60 | Stroop Colour-Word Task | + |

| | | | | | | |
|---|---|---|---|---|---|---|
| | ($M_{AGE}$ = 24.9) | | | | | |
| Hung et al. (2013) | Young Adults ($M_{AGE}$ = 22.57) | Cycling | Moderate (60-70% HRR) | 20 | Tower of London Task | + |
| Joyce et al. (2009) | Young Adults ($M_{AGE}$ = 23) | Cycling | Moderate (40% MAP) | 30 | Stop-signal Task | + |
| Kamijo et al. (2004) | Male Adults ($R_{AGE}$ = 22-33) | Cycling | Very Light ($M_{HR}$ = 84.43bpm) | 18 | Go/No-Go Task | 0 |
| | | | Moderate ($M_{HR}$ = 118.17) | | | + |
| | | | Very High ($M_{HR}$ = 190.17) | | | 0 |
| Kamijo et al. (2009) | Young Male Adults ($M_{AGE}$ = 21.8) | Cycling | Light (30% $V0_2$max) | 20 | Modified Flanker Task | 0 |
| | | | Moderate (50%$VO_2$max) | | | 0 |
| | Older Male Adults ($M_{AGE}$ = 65.5) | | Light (30% $V0_2$max) | | | 0 |
| | | | Moderate (50%$VO_2$max) | | | 0 |
| Lambourne et al. (2010) | Young Adults ($M_{AGE}$ = 21.1) | Cycling | Moderate (90% $V_{TH}$) | 40 | PASAT | 0 |
| Netz et al. (2007) | Late Middle-Age Adults ($R_{AGE}$ = 50-64) | Treadmill | Moderate (60% HRR) | 44 | Alternate Uses Test | + |
| | | | Moderate (70% HRR) | | | + |
| Sibley et al. (2006) | Young Adults ($M_{AGE}$ =22.5) | Cycling | Moderate ($M_{HR}$ = 151.75 bpm) | 20 | Stroop Colour-Word Task | + |
| Szabo & Gauvin (1992) | Young Male Adults ($M_{AGE}$ = 28.1) | Cycling | Moderate (15 min at 40%HRR, 10 min at 60%HRR) | 25 | Mathematical Problem Solving | 0 |
| Winter et al. (2007) | Young Male Adults ($M_{AGE}$ = 22.2) | Treadmill | Moderate ($HR_{MED}$ = 140) | 40 | Vocabulary Learning Task | 0 |
| | | Treadmill | High-Intensity Intervals ($HR_{MED}$ = 184) | 6 | | + |

Note. $HR_{MED}$ = Median HR, AT = Aerobic Threshold, $M_{AGE}$ = Mean Age, $R_{AGE}$ = Age Range, $V_{TH}$ = Ventilatory Threshold, HRR = Heart Rate Reserve, $M_{HR}$ = Mean Heart Rate, MAP = Maximal Aerobic Power, WCST = Wisconsin Card Sorting Test, PASAT = Paced Auditory Serial Addition Test, CPT = Contingent Continuous Performance Task.

**Acute Effects of Exercise on Executive Function after a Delay Following Exercise**

The previous summary of research on exercise and executive function immediately following exercise showed a mix of results that appear to be moderated by exercise intensity. Results from studies investigating cognitive function performance after a delay following exercise also indicate the relationship between exercise and cognitive function may be moderated by exercise intensity. A summary of studies that have specifically investigated executive function following a delay after exercise is presented in Table 2. Results from two studies provided 1 positive and 3 null effects for low-intensity exercise. A greater body of literature has examined moderate-intensity exercise, as twelve studies have provided 7 positive and 10 null effects. High-intensity exercise demonstrated 1 positive effect and 4 null effects derived from two studies. Two studies examined exercise performed until exhaustion reported 1 positive effect and 6 null effects.

Overall, this review of the literature provides some support for the positive effects that may be derived from exercise for executive functioning following a delay after exercise, however due to the variation in the effect sizes reported, interpretation of these effects requires further elaboration. Several studies demonstrated medium to large effect sizes, which lend further support to the large effect ($g$ = 0.77) for acute exercise on executive function reported by McMorris and Hale (2012). For example, a large positive effect ($d$ = 1.07) was reported by Cordova et al. (2009) and also ($\eta^2$ = 0.44) reported by Hung et al., (2013) when examining moderate-intensity exercise. Large effects were also shown for low ($d$ = 1.96)(Byun et al., 2014) and high-intensity exercise ($d$ =

0.84)(Cordova et al., 2009). A medium effect size was found for low-intensity exercise ($d$ = 0.40)(Cordova et al., 2009). Considered together, the current summary of the research, in concert with three reviews of the literature suggest a positive effect of exercise on executive function performance when assessed after a delay following exercise effect sizes ranging from small to large. Importantly, the results also suggest this relationship may be moderated by exercise intensity.

Table 2

*Studies Examining Executive Function after a Delay Following Exercise*

| Study | Population | Exercise Mode, Intensity and Duration | | | Executive Function Test | Delay After Exercise (minutes) | Direction of Effect |
|---|---|---|---|---|---|---|---|
| | | Mode | Intensity | Duration (minutes) | | | |
| Byun et al. (2014) | Young Adults ($M_{AGE}$ = 20.6) | Cycling | Light (30%$VO_2$max) | 20 | Stroop | 5 | + |
| Heckler & Croce (1992) | Young Female Adults ($M_{AGE}$ = 28.2) | Treadmill | Moderate (~55% $VO_2$max) | 20 | Mental Arithmetic Problem Solving | 5 | 0 |
| | | | | 40 | | | 0 |
| Cordova et al. (2009) | Older Female Adults ($M_{AGE}$ = 63.8) | Cycling | 60% AT | 20 | Tower of Hanoi | 8 | 0 |
| | | | | | Trail Making Test | | 0 |
| | | | | | Verbal Fluency Test | | 0 |
| | | | 90% AT | | Tower of Hanoi | | + |
| | | | | | Trail Making Test | | + |
| | | | | | Verbal Fluency Test | | + |
| | | | 110% AT | | Tower of Hanoi | | 0 |
| | | | | | Trail Making Test | | 0 |
| | | | | | Verbal Fluency Test | | + |
| Tomporowski et al. (2005) | Young Male Adults ($M_{AGE}$ = 22.1) | Cycling | Moderate (60%$VO_2$max) | 40 | PASAT | 10 | 0 |
| Travlos & Marisi (1995) | Young Male Adults ($M_{AGE}$ = 23.0) | Cycling | Progressive Endurance Trial | Exhaustion | Random Number Generation | 10 | 0 |
| Emery et al. (2001) | Older Adult COPD Patients ($M_{AGE}$ = 67.8) | Cycling | Progressive Exercise | Exhaustion | Verbal Fluency Test | 15 | + |
| | | | | | Trail Making Test | | 0 |
| | | | | | Digit Backward Span Test | | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Healthy Older Adults ($M_{AGE}$ = 68.7) | | Progressive Exercise | | Verbal Fluency Test | | 0 |
| | | | | | Trail Making Test | | 0 |
| | | | | | Digit Span Backward Test | | 0 |
| Heckler & Croce (1992) | Young Female Adults ($M_{AGE}$ = 28.2) | Treadmill | Moderate (~55% $VO_2$max) | 20 | Mental Arithmetic Problem Solving | 15 | 0 |
| | | | | 40 | | 15 | 0 |
| Lambourne et al. (2010) | Young Adults ($M_{AGE}$ = 21.1) | Cycling | Moderate (90% $V_{TH}$) | 40 | PASAT | 15 | 0 |
| Yanagisawa et al. (2010) | Young Adults ($M_{AGE}$ = 21.5) | Cycling | Moderate (50%$VO_2$max) | 10 | Stroop Task | 15 | + |
| Del Giorno et al. (2010) | Young Adults ($M_{AGE}$ = 20.2) | Cycling | Moderate ($V_{TH}$ - 20%) | 20 | WCST | 20 | 0 |
| | | | | | CPT | 20 | 0 |
| | | | High ($V_{TH}$ +10%) | | WCST | 20 | 0 |
| | | | | | CPT | 20 | 0 |
| Szabo & Gauvin (1992) | Young Male Adults ($M_{AGE}$ = 28.1) | Cycling | Moderate (15min at 40% HRR, 10min at 60% HRR) | 25 | Mathematical Problem Solving | 20 | 0 |
| Hung et al. (2013) | Young Adults ($M_{AGE}$ = 22.57) | Cycling | Moderate (60-70% HRR) | 20 | Tower of London | 30 | + |
| Joyce et al. (2009) | Young Adults ($M_{AGE}$ = 23.0) | Cycling | Moderate (40% MAP) | 30 | Stop-signal task | 30 | + |
| Lambourne et al. (2010) | Young Adults ($M_{AGE}$ = 21.1) | Cycling | Moderate (90% $V_{TH}$) | 40 | PASAT | 30 | 0 |
| Hung et al. (2013) | Young Adults ($M_{AGE}$ = 22.57) | Cycling | Moderate (60-70% HRR) | 20 | Tower of London | 60 | + |

Note. AT = Aerobic Threshold, $M_{AGE}$ = Mean Age, $R_{AGE}$ = Age Range, $V_{TH}$ = Ventilatory Threshold, HRR = Heart Rate Reserve, $M_{HR}$ = Mean Heart Rate, MAP = Maximal Aerobic Power, WCST = Wisconsin Card Sorting Test, PASAT = Paced Auditory Serial Addition Test, CPT = Contingent Continuous Performance Task.

**Theories of the Acute Effects of Exercise on Cognitive Function**

Although substantial literature on the acute effects of exercise on cognitive performance has accumulated, a great deal of it appears to be observational with no consistent use of theory guiding research in the area. One theory that has provided the basis for some of the research on the acute exercise - cognition relationship is the inverted-U theory. Yerkes and Dodson (1908) proposed an inverted-U relationship between the degree of arousal in the organism and information-processing efficiency, whereby performance was least efficient at high and low levels of arousal and reached an optimal point at moderate arousal levels. According to the inverted-U perspective, moderate intensities and durations of exercise should give rise to moderate arousal levels and result in better cognitive performance compared to exercise performed at levels that lead to low and high levels of arousal. This theory provided a foundation for explaining the exercise-cognition relationship that has been expanded with more contemporary cognitive-energetic models.

Cognitive-energetic models propose that physiological and psychological states of wakefulness are a result of exercise-induced arousal due to activation of the reticular-activating system, which modulates ascending projections to the prefrontal cortex (Audriffen, Tomporowski, & Zagrodnik, 2008; Kahneman, 1973; Sanders, 1983). These models elaborate on the general propositions of the inverted-U theory, suggesting cognitive performance is proportional to arousal until an optimal point, after which a decline in performance is seen as a result of heightened arousal (Hockey et al., 1986; Humphreys & Revelle, 1984; Kahneman, 1973; Kamijo et al., 2009; Sanders, 1983).

Several studies have generated support for the view that the acute effects of exercise on cognitive performance operate as an inverted-U function (e.g., Kamijo et al. 2004, Kamijo et al., 2009). However, results of McMorris and Graydon's (2000) review of empirical data did not support this hypothesis. Results of a more recent meta-analysis have further examined this hypothesis and found the inverted-U relationship may only exist for basic cognitive tasks that do not involve executive function (McMorris & Hale, 2012).

Another model that has been applied to understanding the acute effects of exercise on cognitive performance is the reticular-activating hypofrontality (RAH) model (Dietrich & Audriffen, 2011). Although it must be acknowledged that this neurocognitive model was proposed in order to explain cognitive performance during an acute bout of exercise, extension of this model to explain what occurs upon immediate cessation of exercise may be warranted. The RAH model features a two-step process, beginning with the reticular-activating process and transitioning into the hypofrontality process. In terms of cognitive processing parameters, the reticular-activating process serves to interpret implicit information processing, functioning as a product of interrelated arousal systems. Evidence in support of this process suggests that acute exercise facilitates arousal and activation, ultimately speeding up basic bottom-up cognitive processes such as reaction speed. On the contrary, the hypofrontality process involves control over explicit higher-order executive functions. The hypofrontality process proposes that sufficiently strenuous activity requires frontal resources; the use of which will have detrimental effects on cognitive performance (Dietrich, 2006; Dietrich & Sparling, 2004).

According to Dietrich (2003), human consciousness operates in a hierarchical manner. Functions responsible for biological processes (e.g., body movement) are located at the bottom of this hierarchy, whereas executive functions are located at the top. Given that metabolic brain resources are fixed (Ide & Secher, 2000), the hypofrontality perspective proposes the resources available for the processing of executive functions are reduced because a large amount of brain resources are occupied in controlling bodily movements during exercise (Ide & Secher, 2000). Therefore, an individual`s executive function performance should be temporarily reduced during exercise due to the allocation of resources necessary to keep the body in motion while exercising at any level of intensity and regardless of the duration of exercise performed. However, the intensity necessary to induce hypofrontality has not been determined empirically.

Dietrich (2006) further proposes that motor cortex activation necessary for performing exercise will cease upon termination of a bout of exercise, thus enabling the brain to restore crucial metabolic resources to the frontal areas and halt the cognitive decrements caused by hypofrontality. Previous research has supported the prediction that metabolic recovery occurs within seconds to minutes following termination of exercise (Ide, Schmalbruch, Quistorff, Horn, & Secher, 2000). Although there is rapid restoration of these metabolic resources, arousal levels have been found to remain elevated for several minutes following completion of high-intensity steady-state exercise and progressive exercise tests performed until exhaustion (Audriffen et al., 2008; Lambourne & Tomporowski, 2010; Tomporowski, 2003). As increased arousal levels have been witnessed up to nearly an hour into recovery following high-intensity exercise (e.g.

Hillman, Snook & Jerome, 2003), an extended window of increased executive function performance may exist as it takes longer for heightened arousal to dissipate to levels seen at rest.

Together, the inverted-U and RAH perspectives allow for theory-based interpretation of prior evidence in the exercise-executive function area and allow for theory-based predictions for future studies. Although the RAH model may adequately account for acute effects of exercise following light or moderate intensity exercise, it stands to reason that metabolic deficits caused by higher-intensity exercise persist during recovery and lead to short-term decrements in executive function during the acute post-exercise period. The carry-over of metabolic deficits may be further exacerbated by high levels of arousal that should not dissipate immediately following exercise and could further compromise executive function performance immediately after exercise as would be predicted by the inverted-U theory. Thus, based on theory, it could be predicted that high-intensity exercise may lead to impairments in executive function performance immediately following exercise. However, during post-exercise recovery, the metabolic deficits associated with high-intensity exercise should return to normal (Ide et al., 2000), while residual arousal levels should also decline. Indeed, following high-intensity exercise, arousal levels may be expected to fall to moderate levels, while they may return to resting levels following moderate or lighter-intensity exercise. Thus, theory would allow for predictions that high-intensity exercise may lead to better executive function performance during recovery (i.e., moderate arousal) compared moderate or low intensity exercise (i.e., low arousal). In summary, existing empirical data and extensions of theory warrant further investigation of the effects of varying exercise intensities on executive function performance as well as the time course following exercise, over which differential effects may be observed depending on the timing of the executive function performance assessments.

**Acute Effects of Exercise on Executive Function – Is there a Role for HIT?**

Within the literature on executive function and exercise, studies have generally utilized cardiovascular aerobic exercise tasks involving cycling or running (See Tables 1 and 2), with some recent studies investigating the exercise-executive function relationship with resistance exercise (Chang & Etnier, 2009a; 2009b) and isometric exercise (Brown & Bray, in press). However, one alternative mode of aerobic exercise that has begun to receive research attention is high-intensity interval training (HIT).

HIT consists of short sessions (e.g., 20 minutes) involving repeated bursts of intense exercise (~90% $HR_{max}$) separated by periods of rest or lower-intensity exercise (e.g., 1-minute high-intensity; 1-minute lower-intensity). HIT has consistently been shown to induce numerous metabolic, performance and health adaptations traditionally seen following high-volume (60-minute sessions) moderate-intensity endurance exercise (Gaesser & Angadi, 2011; Gibala & McGee, 2008).

One of the most common reasons why people do not participate in regular exercise is a perceived “lack of time” (Godin et al., 1994). However, recent evidence suggests that this problem can be overcome by promoting short duration, HIT (Gaesser & Angadi, 2011; Gibala & McGee, 2008; Gibala, Little, MacDonald & Hawley, 2012; Linke, Gallo, & Norman, 2011). The attractiveness of this method of exercising is that it is time-efficient and can be easily incorporated into one's daily schedule, making exercise participation more feasible (Gaesser & Angadi, 2011; Gibala & McGee, 2008; Linke et al., 2011).

To date, research investigating the impact of an acute bout of HIT on executive function is sparse, with only two studies having utilized this form of exercise stimulus. Given that HIT is performed (at times) at a very high intensity level, it could be expected that HIT would impart similar effects on executive function performance to those associated with high-intensity steady-state exercise. However, it should also be noted that an effective HIT protocol allows for recovery periods following each high-intensity interval, which results in the overall work performed in an exercise session being similar to that of a steady-state moderate intensity bout of exercise. Therefore, it could be expected that the rest periods between intervals provide a sufficient means to recoup resources that are intermittently allocated to the high-intensity exercise stimulus as well as tempering arousal levels. As a result, executive function performance levels may be similar to those that might be expected after performing an acute bout of steady-state moderate-intensity exercise. Previous research has demonstrated positive effects on different indices of executive functioning following HIT (see Table 1; Alves et al., 2014; Winter et al., 2007), which suggest an acute bout of HIT may facilitate executive function. However, further research is required to contrast the effects of HIT with other forms of steady-state exercise and assess the generalizability of these findings to different indices of executive function as well as different populations (e.g., participants in Alves et al.'s study were older adults).

**Statement of the Problem**

While the literature examining the acute effects of exercise on executive function is growing, studies examining this relationship remain limited and provide inconclusive results. The current state of the literature is not only a product of the limited investigation of different executive functions and the time point of examination (i.e. immediately, following a delay after exercise), but also the modality, duration, and intensity of the exercise bout employed. The purpose of this study was to examine the acute effects of 20-minutes of stationary cycling exercise at varying exercise intensities on executive function performance immediately following exercise as well as after 10 and 30-minute delays following exercise.

## HYPOTHESES

**Executive Function Performance Immediately Following Exercise**

**Hypothesis 1.** Based on previous research that revealed a large positive effect ($g$ = 0.77) for acute exercise on executive function (McMorris & Hale., 2012), it was hypothesized that exercise should elicit a positive effect on executive function performance. Based on the review of exercise-executive function effects immediately following exercise (see Table 1), it was predicted there would be a null effect for low-intensity exercise and medium to large positive effects for moderate and high-intensity exercise. Based on previous research by Alves et al. (2014) revealing a medium positive effect of HIT on executive function (Alves et al., 2014) and due to the nature of a HIT workload better reflecting that of a moderate-intensity steady-state bout of exercise, it was hypothesized that executive functioning performance will resemble the effects of moderate-intensity exercise and show a medium positive effect.

**Executive Function Performance 10-minutes Post-exercise**

**Hypothesis 2.** After a 10-minute delay following exercise, it was hypothesized that a medium to large positive effect would be observed. In line with the findings of McMorris and Hale (2012) and the review of studies examining executive function following a delay of up to 20 minutes after exercise (see Table 2), it was hypothesized there would be a medium to large positive effects for low, moderate and high-intensity exercise. In regards to HIT, executive functioning performance was expected to be similar to that of a moderate-intensity bout of steady-state exercise and show a medium positive effect.

**Executive Function Performance 30-minutes Post-exercise**

**Hypothesis 3.** Few studies have investigated acute effects of exercise on executive function beyond 20 minutes. Again, based on the effect size ($g$ = 0.77) reported by McMorris and Hale (2012), it was hypothesized that executive function performance should remain facilitated at 30-minutes post-exercise. However, it was expected that the effect sizes will be smaller than those seen at 10-minutes post-exercise, as arousal levels should decline during the extended interval between exercise cessation and the executive function assessment. Specifically, it was hypothesized that there would be small to medium positive effects for low, moderate and high-intensity exercise as well as HIT at 30-minutes post-exercise.

# METHOD

## Participants and Design

Eighty-eight university students (*n* = 41 men, *n* = 47 women) participated in this study (refer to Table 3 for additional descriptive information about the sample). The design was a 4-group between-subjects design with repeated measures of the executive function performance dependent variables at baseline, immediately following exercise, 10-minutes post-exercise, and 30-minutes post-exercise. The sample size recruited was based on baseline to post-exercise comparisons (immediately post-exercise and following a delay of 10-minutes after exercise cessation) with anticipation of large effect sizes for the moderate and high intensity exercise groups (McMorris & Hale, 2012) of $g = 0.77$. According to estimates provided by Cohen (1992), 18 participants per group are needed for a 4 group ANOVA with alpha of .05, power of .80 and an anticipated large effect size, therefore, 22 participants per group was considered satisfactory.

Due to the potentially strenuous nature of the exercise tasks, the inclusion criteria required all participants to self-report as being recreationally active and willing to engage in strenuous exercise. However, to avoid potential confounding due to extremely high fitness levels, participants were excluded from the study if they were trained or competitive athletes or currently engaged in a formal exercise training program. Participants provided written informed consent and were screened prior to participation for contra indicators of performing executive function tasks and vigorous intensity exercise via the Physical Activity Readiness Questionnaire (PAR-Q; Thomas, Reading, &

Shephard, 1992). The McMaster Research Ethics Board (MREB) approved the research protocol prior to any recruitment and data collection.

**Measures**

**Demographic, physiological and anthropometric data.** Demographic measures included self-reported gender and age. Physiological measures included resting HR which was recorded using a Polar heart rate monitor (HR monitor, Polar S625X) following 5 minutes of silent rest in order to ensure there were no between-group differences in HR, as resting HR is a correlate of cardiovascular fitness (Astrand & Rodahl, 1970). Anthropometric data included height and weight, which were obtained using a standard weigh scale and tape measure, providing a calculation of BMI (mass(kg)/(height(m))$^2$.

**Graded cardiovascular exercise test.** All participants completed a graded exercise test (GXT) on a cycle ergometer (Lode Corival, Groningen, The Netherlands). This test was performed to determine participants' peak workload ($W_{max}$) in order to predict their $VO_2max$, which was utilized for group stratification and to determine the target workload requirements (% of maximum Watts [$W_{max}$] achieved on the test) for the HIT and moderate-intensity exercise conditions if participants were to be randomized to those study conditions.

The GXT consisted of cycling for a 2-minute warm-up at 50W resistance at a self-determined cadence that was > 50 RPM, after which resistance was automatically increased by 1W every 2 seconds until volitional termination of the test by the participant or the point at which their pedal cadence fell below 50 RPM. Peak power output ($W_{max}$)

was obtained by the Lode Ergometry Manager (Lode, The Netherlands) and used to calibrate the exercise protocols on visit two. This method is commonly used in studies involving submaximal aerobic exercise protocols (e.g., Joyce et al., 2009) and the GXT is found to provide a simple, accurate prediction of $VO_2max$ based on highest work rate achieved without utilizing measurements of ventilatory gas consumption and production (Brawner, 2007). The absolute $VO_2max$ value for each participant was determined by applying the following formula: $VO_2max(L/min) = (0.01141 \text{ x } W_{max} + 0.435)$(Hawley & Noakes, 1992). Hawley & Noakes' (1992) predictive equation demonstrated a highly significant ($r = 0.97$) relationship between $VO_2max$ (L/min) and peak workload ($W_{max}$). In order to control for differences in body mass (kg), absolute VO2max (L/min) was then used to calculate relative $VO_2max$ (mL/min/kg) using the following equation: $VO_2max(mL/min/kg) = VO_2max(L/min)*1000/kg$.

**Tests of Executive Functions**

Multiple measures of executive functions are available that provide discrete assessments of working memory, task switching and response inhibition (Chan, Shum, Toulopoulou & Chen, 2008). The two tasks we selected were the Stroop interference task and a stop-signal paradigm. The Stroop task was selected because it is one of the most utilized assessments of executive function performance in the literature (MacLeod, 1991; Stroop, 1935), as well as a common measure that has been used in studies of the effects of exercise on executive function (e.g., Byun et al., 2014; Ferris, Williams, & Shen, 2007; Sibley, Etnier, & Le Masurier, 2006; Yanagisawa et al., 2010). The Stroop task assesses information processing, executive abilities, selective attention and response inhibition

(Pachana, Thompson, Marcopulos & Yoash-Gantz, 2004). The stop-signal paradigm assesses response inhibition (Lappin & Eriksen, 1966; Logan & Cowan, 1984; Verbruggen, Logan & Stevens, 2008) and has also been used in previous research investigating effects of exercise on executive function (e.g., Joyce et al., 2009).

**Stroop task.** Participants performed a modified, computerized version of the Stroop task (Presentation$^{TM}$ software version 17.0; NBS www.neurobs.com). The trial set consisted of a total of 108 trials. During each trial, participants were shown either numeric words (i.e., one, two, or three) or non-numeric, neutral words (e.g., any, great) in various combinations and instructed to identify the number of stimuli words displayed on the screen by pressing the keys for 1, 2 or, 3 on the keyboard. The words were displayed in three different patterns consisting of congruent, incongruent, or neutral numeric word sets. For congruent patterns, the number of the stimulus word and the number of stimuli are the same (e.g., "two two") and requires the participant to press the key for the number "2" on the keyboard. For incongruent patterns, the stimulus word and the number of stimuli are not the same (e.g.,"three three"), in which cases, the correct response requires the participant to press the key for the number "2" and inhibit a response to press the number "3". For neutral word patterns the stimulus word and the number of stimuli are not the same (e.g.,"any any"), in which cases, the correct response requires the participant to press the key for the number "2". However, because the stimulus word is not a number there is no requirement to inhibit a response to press a number key.

The stimuli were presented on a 19" flat screen computer monitor with a 2000 ms window allocated to execute a response for each trial. There was an equal distribution of congruent (*n* = 36), incongruent (*n* = 36) and neutral (*n* = 36) trials presented in random sequence. Participants were instructed to respond as quickly and accurately as possible to each stimulus. Presentation™ software provided two main outcome measures to assess executive function performance: total errors and response time. Throughout the task, the computer recorded the total errors by calculating the number of incorrect responses made on all trials. Response time was calculated as the average time elapsed between the onset of stimulus presentation and execution of the key press response for all trials.

**Stop-signal task.** Participants performed a computerized stop-signal paradigm using Stop-It™ Windows™ executable software (Verbruggen, Logan & Stevens, 2008). The experimental phase consisted of two blocks of 64 trials. The presentation of a fixation sign (+) represented the beginning of each trial after which participants were required to perform a shape judgment task, responding as quickly and accurately as possible on a keyboard by pressing the key for "Z" when presented with the stimulus of a *square* shape and the "/ " key when presented with the stimulus of a *circle* shape. Each trial had a maximal response execution time of 1,250 ms, with each trial separated by intervals of 2,000 ms, independent of the participants' response time. On all trials, participants were instructed to respond as quickly and accurately as possible. On 75% of the trials, the on-screen stimuli were simply presented in silence; while on 25% of the trials the stimulus was followed by an auditory stop signal (beep) referred to as the stop-signal delay (SSD). On the SSD trials, participants were instructed to withhold their responses and press no key on the keyboard. The normal and SSD trials were presented in random sequence.

The Stop-It™ test also incorporates the "horse-race" model (Logan & Cowan, 1984) to ensure participants stop half of their responses. In order to accomplish this, the software automatically adjusts the SSD continuously using a staircase tracking procedure so that when inhibition is successful, SSD increases by 50 ms, however, when inhibition is unsuccessful, SSD decreases by 50 ms. This adjustment not only controls for performance in the stop-signal paradigm, but also provides an estimate of the covert latency of the stop process (stop-signal response time; SSRT). The Analyze-It™ program runs in parallel with the Stop-It™ software, providing an output score for response inhibition performance which is presented as an estimate of the SSRT by subtracting the mean SSD from mean no-signal response-time (Logan, Schachar, & Tannock, 1997). For example, a participant whose mean SSD was 250.00 and mean no-signal response time was 450.00, the SSRT would be 200.00.

**Exercise Manipulations**

For the performance of the GXT and all exercise manipulations, the cycle ergometer was set in hyperbolic (rpm-independent) mode to ensure the workload was kept constant regardless of pedaling speed. This procedure allowed participants to pedal at a speed that was comfortable for them, individually, while ensuring the workload requirements of the cycling tasks were consistent across participants within each study condition.

**High-intensity interval exercise**. Participants in this condition performed a 20-minute 10x1 HIT protocol which required them to alternate between cycling for 1 minute at 70% of their $W_{max}$ at a cadence between 90-120 RPM during the high-intensity cycling interval and a cadence >50 RPM for 1 minute at 12.5% of their $W_{max}$ during the rest interval. Similar protocols have been utilized in several studies with the aim of eliciting ~90% of $HR_{max}$ during the intervals (Gillen, Little, Punthakee, Tarnopolsky, Riddell, & Gibala, 2012; Gillen, Percival, Ludzki, Tarnopolsky & Gibala, 2013; Little, Safdar, Wilkin, Tarnopolsky & Gibala, 2010; Little et al., 2011).

**High-intensity steady state exercise.** Participants in this condition performed a 20-minute cycling protocol at a cadence between 60-90 RPM with the workload resistance adjusted continuously to elicit ~90% of $HR_{max}$, matching the arousal requirements of the HIT condition.

**Moderate-intensity steady state exercise**. Participants in this condition performed a 20-minute cycling task at a cadence of 60-90 RPM at a fixed workload resistance matching the average workload required for the HIT condition. In order to match the HIT workload, the workload was set at a level calculated as follows: $((10_{min} \text{ x } 12.5\%W_{max}) + (10_{min} \text{ x } 70\%W_{max})) / 20_{min}$ = Fixed Workload. For example, a person whose $W_{max}$ is 200W would cycle at a fixed workload of 82.5W ([250W + 1400W]/20 = 82.5W).

**Low-intensity steady-state exercise**. Participants in this condition performed a 20-minute cycling task at a cadence of 60-90 RPM at a fixed workload of 10W in order to simulate (control for) the rudimentary mechanical demands of exercising on a stationary cycle.

**Manipulation Checks**

**Heart rate (HR)**. HR was monitored continuously throughout the exercise protocol using a Polar heart rate monitor (HR monitor, Polar S625X). For analysis purposes, HR was represented by the mean values at 30-second intervals during the exercise protocol. HR ratings were averaged across the exercise session to provide the measure $HR_{AVERAGE}$ and the highest rating during the protocol was recorded as $HR_{PEAK}$.

**Ratings of perceived exertion (RPE).** Borg's RPE scale was used to assess perceived exertion (Borg, 1982). The scale provides participants with a continuum of exertion ratings ranging from 6 (no exertion at all) to 20 (maximal exertion). Participants provided RPE ratings at 30-sec intervals throughout the exercise protocol. In addition to plotting the RPE values for each 30-second interval, the RPE ratings were averaged across the exercise session to provide the measure $RPE_{AVERAGE}$ and the highest RPE rating during the protocol was recorded as $RPE_{PEAK}$.

**Procedure**

Participants visited the lab for testing on two occasions. During the first visit, participants completed the informed consent, PAR-Q, and, the demographic questionnaire. Next, height and weight were assessed and the participant was fitted with a heart rate monitor and instructed to sit quietly for 5 minutes to ensure the device was functioning properly and to obtain their resting heart rate. In order to ensure participants comprehended the nature of the executive function tasks, and performed them correctly, they performed a standard number of practice trials for each test and verbally confirmed their understanding of the task following practice. The researcher then confirmed the tests were performed appropriately by examining the results of the practice trials.

Upon completion of the practice trials, baseline measures were then taken for the Stroop and Stop-It$^{TM}$ tasks. Participants then completed the GXT. Upon completion of the GXT, participants cycled for 3-minutes at a fixed resistance of 50 watts as a cool down and were scheduled for the second lab visit at approximately the same time of day and no less than 48 hours later to allow for recovery from the GXT.

Prior to visit two, participants were stratified by gender and physical fitness as determined by their predicted $VO2_{max.}$ Men were stratified to lower and higher fitness based on a normative $VO2_{max}$ value of 51.5 mL/min/kg. That is, men with a $VO2_{max}$ value equal to or greater than 51.5 mL/min/kg were categorized as having higher fitness, whereas, those with a $VO2_{max}$ value of less than 51.5 mL/min/kg were classified as having lower fitness. As for women, stratification to lower and higher fitness was based on a normative $VO2_{max}$ value of 48 mL/min/kg. Women with a $VO2_{max}$ value equal to or greater than 48 mL/min/kg were classified as having higher fitness, whereas, a $VO2_{max}$ value of less than 48 mL/min/kg were categorized as having lower fitness. Following stratification, participants were randomized to one of the four exercise conditions. Prior to exercise, participants were fitted with a heart rate monitor and sat quietly for 2 minutes to ensure the monitor was working properly. Participants then performed a 3-minute warm-up on the cycle ergometer at a fixed resistance of 12.5% of their $W_{max}$ (low-intensity). Next, participants completed the acute exercise protocol they were randomized to for 20 minutes. During the exercise protocol, HR and RPE were recorded at 30-second intervals. Following the acute exercise session, participants performed a two-minute cool down on the cycle ergometer at a fixed resistance of 12.5% of their $W_{max}$. At the conclusion of the cool-down, participants dismounted from the cycle ergometer and were seated at an adjacent desk. At this point, executive function tests were administered immediately following exercise, followed by a 2-minute rest interval, followed by the executive function tests at 10-minutes post-exercise and a 12-minute rest interval, followed by the executive function tests at 30-minutes post-exercise (refer to Figure 1 for the Session 2 timeline). During breaks between executive function test administration, participants were seated in a comfortable chair in the laboratory and provided a collection of popular magazines (not fitness-, sport- or health-related) to read. At the completion of the experiment, participants were provided with a debriefing letter and thanked for their time and contribution to the project. Throughout the experimental procedure, experimenters only interacted with participants to provide instructions, to take measures, and to ensure the safety of participants during the procedure. There was no verbal/motivational encouragement provided by the experimenters at any time.

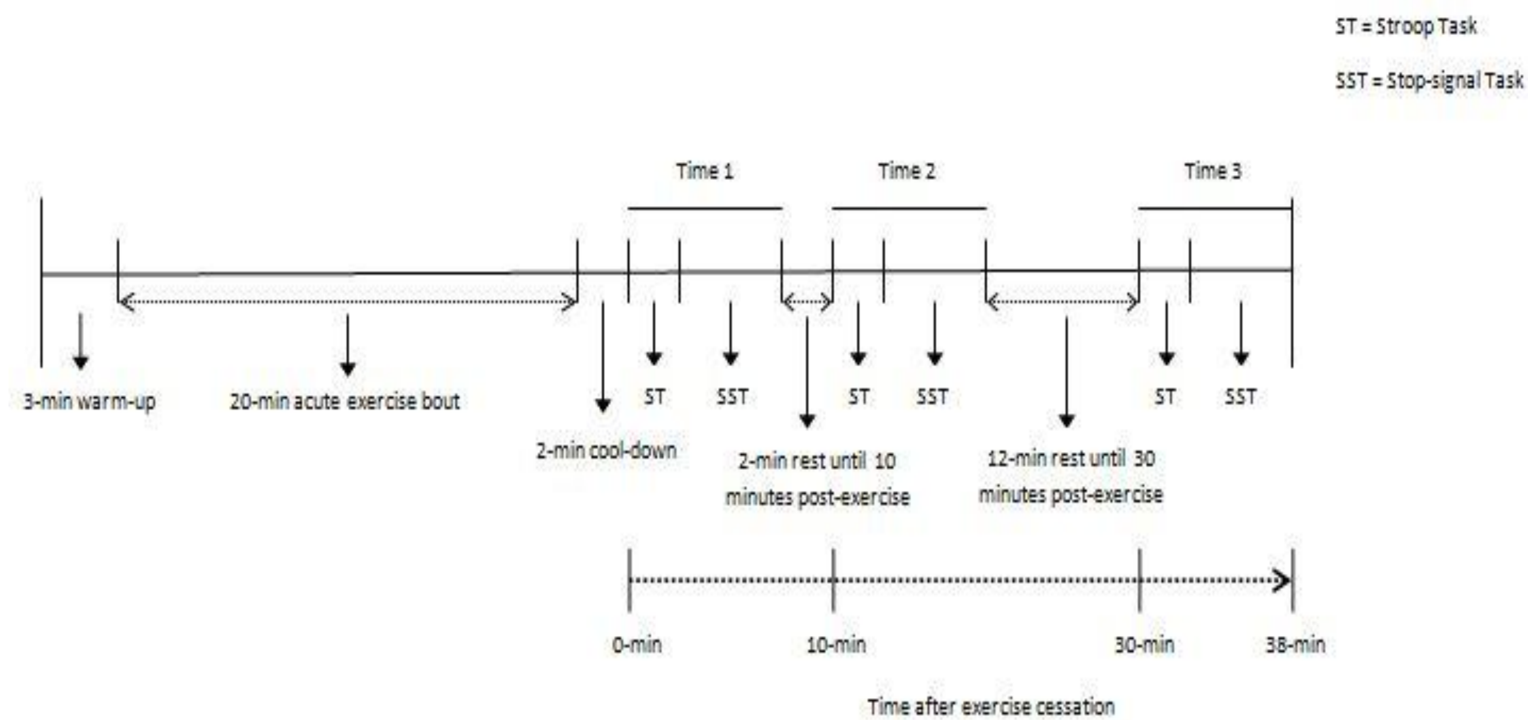


*Figure 1*. Time course of acute exercise and executive function testing during the primary testing session (Session 2).

**Data Analysis**

The effects of the study manipulations on HR and RPE were assessed using separate oneway ANOVAs, comparing groups during the acute bout of exercise. To evaluate between group differences in executive function performance, raw change scores were computed by subtracting Session 1 baseline scores for Stroop errors, Stroop response time (RT), and SSRT from the score immediately following exercise and at post-10 and post-30 minutes of exercise to provide executive function performance measures for the three time points.

To evaluate the hypotheses, separate oneway ANOVAs were computed to compare between-groups performance on each executive function measure at each post-exercise time point. Tukey post-hoc tests were performed on each significant ANOVA result. To further evaluate the main hypotheses, within-person differences between baseline and follow-up executive function performance measures were assessed using one-sample *t*-tests with a criterion comparison value of "0" representing no effect. For all analyses, significance was set at $p < .05$. All statistical analyses were performed using IBM SPSS version 20.

# RESULTS

## Data Screening and Tests for Normality

Standard methods of screening SSRT data were employed as recommended by the developers of the Stop-It™ program (Verbruggen et al., 2008). In accordance with the results from Monte Carlo simulations of Band, Van Der Molen and Logan (2003), SSRT estimates for non-centralized SSDs (i.e., SSDs for which *p*[respond|signal] is significantly different than .50) were excluded from the analysis due to lack of reliability. This resulted in 18, 20 and 18 cases being removed from the immediate post-exercise, post-10 and post-30 analyses, respectively. For change in SSRT, one outlier was removed from immediate post-exercise analysis for having a score greater than 3 standard deviations from the mean. Upon closer inspection of the Stroop RT data, one participant was removed for showing unusual performance characterized by an extreme speed/accuracy trade-off. For change in Stroop RT, there were 2, 3, and 2 outliers removed from the immediate post-exercise, post-10, and post-30 analyses, respectively. In each instance, participants had scores greater than 3 standard deviations from the mean. Prior to analysis, the screened data for main dependent variables: change in SSRT, change in Stroop RT, and change in Stroop total errors, were inspected for skewness and kurtosis and found to be within acceptable ranges (skewness = -0.59 - 0.18; kurtosis = -0.13 - 2.06) according to the recommendations of Tabachnick and Fidell (2001).

## Preliminary Analyses

Participants' scores on demographic, anthropometric and physiological measures were assessed to check for equivalency across groups and the effectiveness of the stratification and randomization protocol (see Table 3). One-way ANOVAs revealed no significant differences between conditions on age, $F$ (3, 84) = .51, $p$ > .20, BMI, $F$ (3, 84) = 1.74, $p$ > .10, resting HR, $F$ (3, 84) = 2.54, $p$ > .05, peak workload, $F$ (3, 84) = .56, $p$ > .20, or $VO2_{max}$ $F$ (3, 84) = 1.02, $p$ > .20. Based on these findings, the randomization protocol was deemed effective.

Table 3

*Age, BMI, Resting HR, Peak Workload and VO2max by Condition*

| | High-Intensity<br>*n* = 22<br>M (SD) | Moderate-Intensity<br>*n* = 22<br>M (SD) | Low-Intensity<br>*n* = 22<br>M (SD) | HIT<br>*n* = 22<br>M (SD) |
|---|---|---|---|---|
| Age (years) | 19.68 (1.91) | 20.09 (1.87) | 19.45 (1.74) | 19.95 (1.96) |
| BMI | 22.76 (3.83) | 23.90 (3.88) | 21.86 (2.36) | 22.05 (2.79) |
| Resting HR (bpm) | 67.72 (9.06) | 67.05 (10.51) | 61.95 (8.73) | 68.68 (6.65) |
| Peak Workload ($W_{max}$) | 240.64 (60.81) | 263.36 (62.13) | 249.82 (56.23) | 245.05 (66.29) |
| $VO_{2max}$ (mL/min/kg) | 48.90 (6.25) | 48.20 (8.16) | 48.35 (7.24) | 51.24 (3.82) |

Note. bpm = beats per minute, $W_{max}$ = Maximum Watts

**Manipulation Checks**

Figure 2 shows the average HR response for each group at 30-sec intervals during the bouts of exercise. Mean HR ($HR_{AVERAGE}$) values from the exercise bout are presented by condition in Table 4. Results of a oneway ANOVA showed a significant between-group difference, $F$ (3, 84) = 139.34, $p < .001$. Post-hoc (Tukey) tests revealed significant differences ($p < .05$) between all groups. Peak HR ($HR_{PEAK}$) values from the exercise bout are presented in Table 2. A oneway ANOVA showed a significant between-group difference, $F$ (3, 84) = 143.52, $p < .001$. Post-hoc (Tukey) tests revealed a significant difference between all groups ($p < .001$), with the exception of the difference between the HIT and high-intensity groups ($p > .20$).

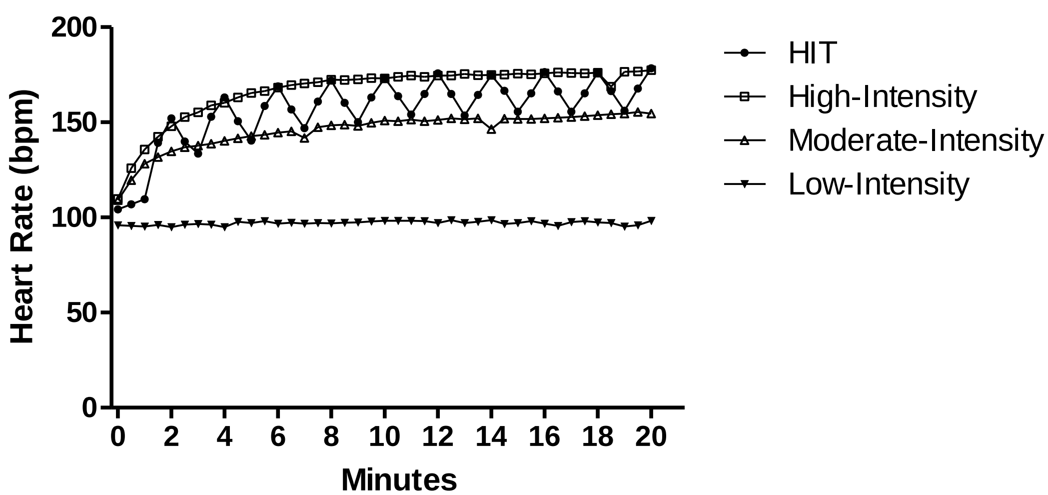


*Figure 2*. Heart rate at 30-second intervals over 20 minutes of exercise by condition.

The average RPE scores for each group at 30-sec intervals during the bouts of exercise are illustrated in Figure 3. Mean RPE ($RPE_{AVERAGE}$) and Peak RPE ($RPE_{PEAK}$) values from the exercise bouts are presented by condition in Table 4. Results of a oneway ANOVA of Mean RPE showed a significant between-group difference $F$ (3, 84) = 56.39, $p < .001$. Post-hoc Tukey tests revealed a significant difference between all groups ($p < .01$), with the exception of the difference between the HIT and moderate intensity conditions ($p > .20$). A oneway ANOVA of Peak RPE revealed a significant difference between-groups, $F$ (3, 84) = 62.86, $p < .001$ with post-hoc Tukey tests demonstrating all groups significantly differed ($p < .01$) with the exception of the difference between the HIT and high-intensity conditions ($p > .20$).

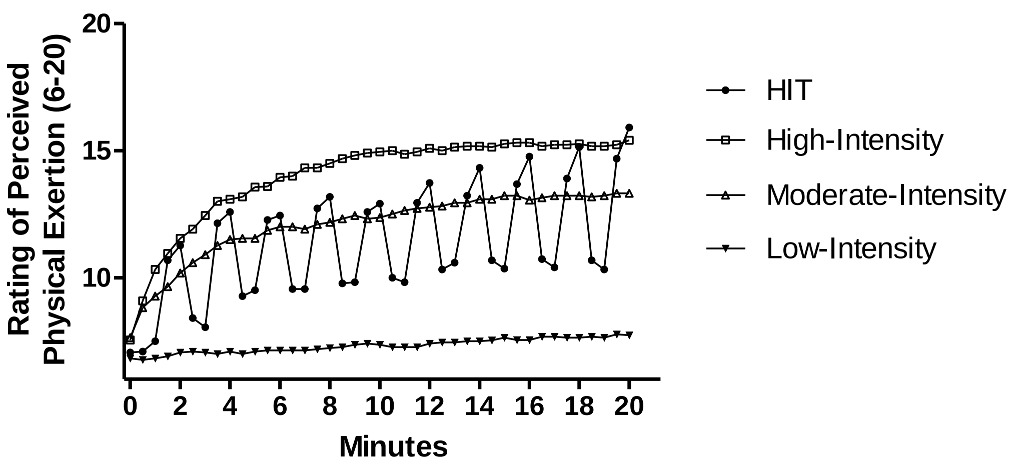


*Figure 3*. Ratings of perceived physical exertion at 30-second intervals over 20 minutes of exercise by condition.

In summary, the results of the manipulation checks corroborated our intended manipulations. $HR_{AVERAGE}$ showed significant differences, increasing linearly with exercise intensity. As expected, $HR_{AVERAGE}$ values for the HIT group were between the values observed in the moderate and high-intensity groups due to nature of their rest-to-work protocol. Furthermore, $HR_{PEAK}$ and $RPE_{PEAK}$ were progressively and significantly greater ($p < .01$) with increasing exercise intensity with the exception of the similar scores for the HIT and high-intensity groups, which were consistent with the intended effects of the manipulations. Lastly, $RPE_{AVERAGE}$ was also significantly greater with increasing intensity ($p < .05$), with the exception of the HIT and moderate intensity group. This is consistent with the fact that both groups experienced an equivalent average workload (W) over the 20-minute exercise bout.

Table 4

*Summary Statistics for HR Average, RPE Average, HR Peak, and RPE Peak During Exercise by Condition.*

| | High-Intensity<br>$n$ = 22 | Moderate-Intensity<br>$n$ = 22 | Low-Intensity<br>$n$ = 22 | HIT<br>$n$ = 22 | $F$ |
|---|---|---|---|---|---|
| HR Average | 167.96 (12.52)$_a$ | 146.63 (13.13)$_b$ | 97.02 (13.71)$_c$ | 157.76 (10.35)$_d$ | 139.34* |
| RPE Average | 14.16 (1.98)$_a$ | 12.19 (2.43)$_b$ | 7.33 (1.27)$_c$ | 11.45 (1.21)$_b$ | 56.39* |
| HR Peak | 179.86 (11.82)$_a$ | 158.41 (15.44)$_b$ | 106.23 (15.68)$_c$ | 179.59 (10.67)$_a$ | 143.52* |
| RPE Peak | 16.41 (2.28)$_a$ | 13.77 (3.05)$_b$ | 7.91 (1.72)$_c$ | 16.41 (2.24)$_a$ | 62.86* |

Note. Standard deviations are in parenthesis. * = $p < .001$. HR values are in beats per minute. Values in the same row that do not share same subscript are significantly different at $p < .05$.

## Hypothesis Tests

### Executive Function Performance Immediately Following Exercise

Table 5 shows the descriptive statistics for all variables immediately post-exercise. Results of a oneway ANOVA showed there was a significant effect of exercise intensity on Stroop RT, $F$ (3, 81) = 2.97, $p < .05$. Post-hoc Tukey tests between conditions revealed a trend indicating faster response speeds for the high-intensity ($p$ = .06) and moderate-intensity ($p$ = .08) conditions in comparison to the low-intensity condition. Within-group, one sample t-tests for Stroop RT showed significant improvements from baseline for the high-intensity ($p$ = .02, $d$ = 0.53) and moderate-intensity ($p < .001$, $d$ = 0.96) conditions, while there were no significant improvements from baseline in the HIT and low-intensity conditions.

A oneway ANOVA revealed no significant effect of exercise intensity for Stroop total errors, $F$ (3, 84) = 1.475, $p > .20$. Within-group, one sample t-tests revealed a significant reduction in Stroop total errors in the high-intensity condition ($p$ = .005, $d$ = 0.69), with no other groups showing differences from baseline ($p > .10$).

A oneway ANOVA showed no between-group effects for SSRT, $F$ (3, 65) = 1.208, $p > .20$. Within-group, one sample t-tests showed a significant improvement in SSRT for the HIT condition ($p$ = .009, $d$ = 0.71). Additionally, the low-intensity condition showed a near significant trend ($p$ = .072, $d$ = 0.46) for improvement, yet no improvements were seen in the high and moderate intensity conditions ($p > .20$).

Table 5

*Summary Statistics for Stroop RT, Stroop Total Errors, and SSRT at Baseline, Immediately Post-exercise, and Immediately Post-exercise – Baseline Differences by Condition.*

| Measure | Condition | Baseline | Immediately Post-exercise | Immediately Post-exercise – Baseline Difference | Cohen's *d* |
|---|---|---|---|---|---|
| Stroop RT (ms) | | | | | |
| | HIT | 555.02 (60.65) | 542.42 (64.32) | -12.60 (35.95) | 0.35 |
| | High-Intensity | 561.91 (77.48) | 527.64 (64.95) | -34.27 (65.24)* | 0.53 |
| | Moderate-Intensity | 539.27 (64.02) | 506.00 (56.57) | -33.28 (35.52)** | 0.96 |
| | Low-Intensity | 535.16 (71.59) | 537.86 (71.46) | 2.70 (46. 27) | -0.06 |
| Stroop Total Errors | | | | | |
| | HIT | 4.73 (3.01) | 4.64 (3.40) | -0.09 (2.27) | 0.04 |
| | High-Intensity | 5.36 (3.59) | 3.91 (2.91) | -1.45 (2.20)** | 0.69 |
| | Moderate-Intensity | 4.68 (4.01) | 3.77 (4.44) | -0.91 (2.74) | 0.34 |
| | Low-Intensity | 3.91 (2.22) | 3.55 (2.58) | -0.36 (2.08) | 0.18 |
| SSRT (ms) | | | | | |
| | HIT | 303.04 (33.01) | 281.42 (25.32) | -21.62 (31.13)** | 0.71 |
| | High-Intensity | 279.77 (33.13) | 268.05 (30.05) | -11.72 (36.01) | 0.33 |
| | Moderate-Intensity | 270.71 (30.77) | 271.67 (23.63) | 0.95 (37.46) | -0.04 |
| | Low-Intensity | 277.08 (34.76) | 258.48 (40.02) | -18.61 (41.12) | 0.46 |

Note. Standard deviations are in parenthesis. Significant within-person differences with a criterion comparison value of "0" representing no effect are indicated as, * $p < .05$, ** $p < .01$.

**Executive Function Performance at 10-minutes Post-exercise**

Descriptive statistics for all variables at Time 2 can be found in Table 6. A oneway ANOVA of the Stroop RT data revealed no significant effect of exercise intensity at 10-minutes Post-exercise, $F$ (3, 80) = .43, $p$ > .20. Within-group, one sample $t$-tests revealed significantly faster Stroop RT for the low-intensity condition ($p$ = .01, $d$ = 0.61), moderate-intensity ($p$ = .004, $d$ = 0.96), and HIT ($p$ = .05, $d$ = 0.47) groups compared to baseline. Stroop RT did not change from baseline to Time 2 in the high-intensity condition ($p$ > .20).

A oneway ANOVA showed no significant effect of exercise intensity for Stroop total errors, $F$ (3, 84) = 1.141, $p$ > .20. Within-group, one sample t-tests revealed significant improvements of Stroop total errors for all groups (all $ps$ < .05), with the exception of the HIT condition ($p$ > .20).

For SSRT, a oneway ANOVA revealed no between-group differences, $F$ (3, 64) = 1.456, $p$ > .20 at Time 2. However, within-group, one sample t-tests showed significantly faster SSRT for the HIT ($p$ = .02, $d$ = 0.59), moderate-intensity ($p$ = .05, $d$ = 0.54) and low-intensity condition ($p$ = .001, $d$ = 0.94), while the high-intensity condition showed no change from baseline.

Table 6

*Summary Statistics for Stroop RT, Stroop Total Errors, and SSRT at Baseline,* 10*-minutes Post-exercise, and 10-minutes Post-exercise – Baseline Differences by Condition.*

| Measure | Condition | Baseline | 10-minutes Post-exercise | 10-minutes Post-exercise – Baseline Difference | Cohen's *d* |
|---|---|---|---|---|---|
| Stroop RT (ms) | | | | | |
| | HIT | 555.02 (60.65) | 538.24 (72.67) | -16.78 (37.40) | 0.47 |
| | High-Intensity | 550.99 (70.33) | 530.29 (80.37) | -20.69 (64.89)* | 0.32 |
| | Moderate-Intensity | 539.27 (64.02) | 506.28 (45.19) | - 32.99 (45.96)** | 0.78 |
| | Low-Intensity | 535.40 (69.88) | 510.38 (55.44) | -25.02 (43.51)* | 0.61 |
| Stroop Total Errors | | | | | |
| | HIT | 4.73 (3.01) | 4.27 (2.90) | -0.45 (3.00) | 0.15 |
| | High-Intensity | 5.36 (3.59) | 3.64 (3.08) | -1.73 (2.76)* | 0.63 |
| | Moderate-Intensity | 4.68 (4.01) | 3.05 (2.08) | -1.64 (2.85)* | 0.74 |
| | Low-Intensity | 3.91 (2.22) | 2.36 (1.73) | -1.55 (1.60)* | 1.02 |
| SSRT (ms) | | | | | |
| | HIT | 303.04 (33.01) | 282.67 (31.88) | -20.37 (34.46)* | 0.59 |
| | High-Intensity | 282.26 (34.16) | 280.33 (40.71) | -1.94 (41.12) | 0.05 |
| | Moderate-Intensity | 278.36 (39.99) | 257.88 (26.45) | -20.48 (39.55)* | 0.54 |
| | Low-Intensity | 280.32 (36.61) | 251.77 (23.72) | -28.54 (32.42)** | 0.94 |

Note. Standard deviations are in parenthesis. Significant within-person differences with a criterion comparison value of “0” representing no effect are indicated as, * $p$ < .05, ** $p$ < .01.

**Executive Function Performance at 30-minutes Post-exercise.**

At 30-minutes post-exercise, all groups continued to show slight improvements (over baseline) for Stroop RT as evident in Table 7. However, results of a oneway ANOVA showed no significant between-group differences, $F$ (3, 81) = .30, $p$ > .20. Results of within-group, one sample t-tests revealed Stroop RT was faster than baseline for the moderate-intensity ($p$ = .007, $d$ = 0.75) and low-intensity conditions ($p$ = .04, $d$ = 0.49), but no significant differences for the HIT and high-intensity groups ($p$ > .10).

A oneway ANOVA of the Stroop total errors at Time 3 showed no significant differences between the groups, $F$ (3, 84) = .15, $p$ > .20. Within-group, one sample t-tests showed lower error scores compared to baseline for the high-intensity ($p$ = .02, $d$ = 0.54) and low-intensity conditions ($p$ = .006, $d$ = .66), while the HIT ($p$ = .063, $d$ = 0.42) and moderate-intensity condition ($p$ = .095. $d$ = 0.40) revealed non-significant trends of improvements over baseline scores.

A oneway ANOVA of the SSRT scores at Time 3 showed no between-group differences, $F$ (3, 67) = .26, $p$ > .20. Results of within-group, one sample t-tests showed SSRT scores were not different from baseline for all groups (all $ps$ > .20).

Table 7

*Summary Statistics for Stroop RT, Stroop Total Errors, and SSRT at Baseline, 30-minutes Post-exercise, and 30-minutes Post-exercise – Baseline Differences by Condition.*

| Measure | Condition | Baseline | 30-minutes Post-exercise | 30-minutes Post-exercise – Baseline Difference | Cohen's *d* |
|---|---|---|---|---|---|
| Stroop RT (ms) | | | | | |
| | HIT | 555.02 (60.65) | 543.81 (65.42) | -11.21 (37.74) | 0.30 |
| | High-Intensity | 554.14 (70.06) | 537.62 (81.40) | -16.52 (80.09) | 0.21 |
| | Moderate-Intensity | 539.27 (64.02) | 513.59 (43.58) | -25.68 (39.39)** | 0.75 |
| | Low-Intensity | 535.40 (69.88) | 512.55 (53.79) | -22.85 (49.05)* | 0.49 |
| Stroop Total Errors | | | | | |
| | HIT | 4.73 (3.01) | 3.55 (3.49) | -1.18 (2.82) | 0.42 |
| | High-Intensity | 5.36 (3.59) | 3.77 (3.13) | -1.59 (3.00)* | 0.54 |
| | Moderate-Intensity | 4.68 (4.01) | 3.59 (2.94) | -1.09 (2.93) | 0.40 |
| | Low-Intensity | 3.91 (2.22) | 2.50 (1.82) | -1.41 (2.15)** | 0.66 |
| SSRT (ms) | | | | | |
| | HIT | 300.00 (31.32) | 296.31 (31.32) | -3.69 (34.42) | 0.11 |
| | High-Intensity | 283.36 (32.35) | 268.07 (46.45) | -15.29 (42.76) | 0.37 |
| | Moderate-Intensity | 278.21 (38.81) | 269.09 (34.53) | -9.12 (52.47) | 0.17 |
| | Low-Intensity | 279.31 (37.40) | 266.75 (30.49) | -12.56 (30.36) | 0.42 |

Note. Standard deviations are in parenthesis. Significant within-person differences with a criterion comparison value of “0” representing no effect are indicated as, * $p < .05$, ** $p < .01$.

# DISCUSSION

The purpose of this study was to examine the acute effects of 20-minutes of stationary cycling exercise at varying intensities on executive function performance and to investigate these acute effects immediately following exercise as well as after 10 and 30-minute delays following exercise. The main findings indicate that an acute bout of aerobic exercise positively influenced performance on the indices of executive function assessed. Simply stated, acute exercise facilitated executive function immediately following exercise and this facilitative effect remained evident at 10 minutes post-exercise and to a lesser degree 30 minutes after the cessation of exercise. Given the hypotheses were linked to the post-exercise timing of the executive function tests, results will be discussed reflecting exercise effects on cognitive performance immediately following, post-10 minutes, and post-30 minutes of exercise.

## Executive Function Performance Immediately Following Exercise

The first hypothesis was that exercise should elicit positive effects on executive function immediately following exercise. In support of the hypothesis, results demonstrated significant medium to large facilitative effects on indices of executive function for the moderate, high-intensity, and HIT conditions. These findings support those of previous studies that suggest improvements in executive function following an acute bout of moderate-intensity exercise (Coles & Tomporowski, 2008; Del Giorno et al., 2010; Hung et al., 2013; Joyce et al., 2009; Kamijo et al., 2004a; Netz, Argov, & Inbar, 2007; Sibley et al., 2006), high-intensity exercise (Ferris et al., 2007; Hogervorst, Riedel, Jeukendrup, & Jolles, 1996), and HIT (Alves et al., 2014; Winter et al., 2007).

It was also hypothesized that HIT would lead to similar effects to those associated with a moderate-intensity bout of exercise; however, results did not support this relationship as the effects of HIT were substantially smaller than those seen in the moderate intensity steady state condition for all indices of executive function with the exception of response inhibition. Despite equalizing the workload of the exercise in the moderate-intensity condition, it may be that HIT provides unique stimuli that affect executive function differently that steady-state moderate- or high-intensity exercise immediately following exercise. These facilitative effects will require further research to more fully understand.

The hypothesis that there would be a null effect of low-intensity exercise on executive function performance was also supported. These findings parallel previous research that has demonstrated null effects following very low and low-intensity exercise (Kamijo et al., 2004a; Kamijo et al., 2009). Together, these results suggest that exercise intensity may need to surpass a threshold of at least moderate-intensity in order to elicit facilitative effects for executive function performance immediately following exercise.

**Executive Function Performance at 10 Minutes Post-exercise**

The second set of hypotheses proposed there would be an overall positive effect for exercise on executive function performance, with medium to large positive effects demonstrated for low, moderate, and high-intensity steady state exercise as well as HIT. Again, it was hypothesized that HIT would elicit beneficial effects for executive function that resemble moderate-intensity exercise. As expected, results revealed significant medium to large effects for improvements in executive function for all conditions. These findings are consistent with other research examining executive function following a brief delay after exercise as improved executive function test performance has been demonstrated following low (Byun et al., 2014), moderate (Cordova et al., 2009; Yanagisawa et al., 2010) and high-intensity exercise (Cordova et al., 2009).

The current study is the first we are aware of to have investigated executive function performance after a 10-minute delay following an acute bout of HIT. Findings supported our hypothesis that executive function performance following HIT would be similar to that observed in the moderate-intensity steady state exercise condition, as both conditions revealed significantly greater response inhibition speed ($p < .05$). In combination with previous studies, our findings demonstrate the facilitative effects of exercise, regardless of intensity for executive function performance that should be expected following a short delay after cessation of exercise.

**Executive Function Performance at 30 Minutes Post-exercise.**

The third set of hypotheses predicted executive function performance would remain facilitated at 30-minutes post-exercise, although the observed effects would be diminished compared to those seen at 10-minutes post-exercise. Specifically, we expected to see small to medium positive effects for executive function performance for low, moderate and high-intensity steady state exercise as well as effects for the HIT condition. Generally, our results supported the hypotheses, with sustained improvements for executive function performance (compared to baseline), although to a lesser degree in comparison to results seen following a delay of 10 minutes after cessation of exercise.

The HIT condition also revealed performance similar to the moderate-intensity condition for two of the three indices of executive function.

Literature examining executive function performance following a delay of 30 minutes or greater after cessation of exercise is sparse. The few studies that have been conducted are also limited to examination of moderate-intensity exercise. Nonetheless, the findings suggest beneficial effects can be anticipated following an extended post-exercise period (Hung et al., 2013; Joyce et al., 2009). The current study provides novel findings indicating the beneficial effects of exercise on executive function may be derived up to 38 minutes following exercise, regardless of intensity.

**A Theory of Acute Effects of Exercise on Executive Function?**

To date, several theories have been proposed to explain the exercise - cognition relationship. Over the past century, the inverted-U theory has received considerable attention with scientists hypothesizing that cognitive performance is proportional to arousal to an optimal point at moderate levels, whereas arousal below or exceeding this point results in suboptimal performance (Hockey et al., 1986; Humphreys & Revelle, 1984; Kahneman, 1973; Sanders, 1983; Yerkes & Dodson, 1908). The current study is the first to have investigated the effects of low, moderate, high and high-intensity interval exercise on executive function performance and also the first to have done so at multiple time points following exercise in a single investigation. Despite the importance of theory to assist in understanding processes and patterns by which exercise may affect cognitive function, our findings support those of consolidated study effects reported in recent meta-analyses that have failed to find evidence for an inverted-U relationship between exercise intensity and executive function performance (Chang et al., 2012; Lambourne & Tomporowski, 2010; McMorris & Hale, 2012). However, given there was not a linearly graded exercise stimulus in the present study, the present data may not be adequate for testing predictions for the inverted-U theory.

As the inverted-U theory may not adequately account for the acute effects of exercise on cognitive function, the present results should also be interpreted in light of Dietrich and Audriffen's (2011) reticular activating hypofrontality model. This neurocognitive model primarily attempts to account for the effects of exercise on cognitive performance while performing exercise, however, its predictions may be extended to predict changes in executive function post-exercise as well. The improvements in executive function performance seen in the current study lend some support to this theory. Specifically, we saw that intensity did not moderate the improvements in executive function immediately following, and after a delay following exercise, suggesting hypofrontality may be reversed rapidly following cessation of exercise. Importantly, these results did not support our hypothesis that executive function would lead to impairments immediately following exercise that were based on recent findings by Del Giorno et al. (2010). In contrast to Del Giorno et al. (2010), executive function was facilitated immediately following high-intensity exercise and was also enhanced immediately following HIT.

Findings also did not support our prediction there would be a latent recovery following high-intensity exercise that might be attributable to metabolic deficits and arousal levels which accompany exercise at a high-intensity. These findings support

Dietrich's (2006) proposal, as hypofrontality does not appear to occur upon termination of exercise, providing individuals with the critical resources needed for improved executive function. Although executive function was not assessed during exercise in the present study, the current findings corroborate previous studies that demonstrate higher-intensity exercise will not have detrimental effects that last beyond termination of exercise (Alves et al., 2014; Ferris et al., 2007; Hogervorst et al., 1996).

**Mechanisms That May Account for Facilitated Executive Function Performance**

Although current theories may not adequately account for the generalized facilitative effects of exercise on executive function performance observed in this study, it is important to also consider more specific mechanisms that occur in the central nervous system as a result of exercise. Recent studies have employed fNIRS measurements to asses neural substrates associated with exercise. Findings have demonstrated that aerobic exercise at moderate and low-intensity results in significant increases in cortical activation in the dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC) and frontopolar area (Byun et al., 2014; Yanagisawa et al., 2010). Studies that have used fNIRS, PET and fMRI to examine Stroop interference effects have also reported activation of the LPFC (most notably the DLPFC) as well as the anterior cingulate cortex (Derrfuss, Brass, Neumann, & Von Cramon, 2005; Ehlis, Herrmann, Wagener, & Fallgatter, 2005; Laird et al., 2005, Schroeter, Zysset, Kupka, Kruggel, & von Cramon, 2002; Schroeter, Zysset, Kruggel, & von Cramon, 2003; Schroeter, Zysset, Wahl, & von Cramon, 2004). Such research suggests LPFC activation that occurs during exercise may translate into better accommodating the interference processing/response inhibition demands required by the Stroop task (Banich et al., 2000, 2001). In the present study, both executive function tasks required participants to overcome interference processing and response inhibition, thus one may posit that the effects revealed in the current study may be a result of LPFC activation. While this does not account for exercise of higher intensities, it does suggest regional cortical activation, which may facilitate executive function following acute bouts of exercise irrespective of exercise intensity.

One further potential biological mechanism that may be implicated in the acute effects of exercise on executive function is brain-derived neurotrophic factor (BDNF). BDNF is a secreted protein distributed throughout the central nervous system (Binder & Scharfman, 2004; Conner, Lauterborn, Yan, Gall, & Varon, 1997; Merlio et al., 1993) which aids in the survival of existing neurons (Acheson et al., 1995) and promotes neurogenesis and synaptogenesis (Huang & Reichardt, 2001). Beyond these neurotrophic effects, BDNF has been found to play a role in higher-order cognitive processes such as learning and memory through facilitation of synaptic plasticity in several brain areas including the hippocampus (Yamada & Nabeshima, 2003). Previous research with animals has revealed that acute exercise leads to up-regulation of BDNF following exposure to short periods of exercise (Vaynman, Ying, Yin, & Gomez-Pinilla, 2004). For humans, increases in serum BDNF have been found in numerous studies involving exercise. For example, Ferris et al. (2007) showed an intensity-dependent relationship between exercise and serum BDNF levels with the highest levels of BDNF being seen alongside high intensity exercise. In that study, Stroop word and colour scores for all conditions increased relative to baseline. However, the largest increase in Stroop colour-word task performance was seen in the high-intensity exercise condition, demonstrating a link between exercise, BDNF and executive function performance.

Griffin et al. (2011) used a similar protocol to Ferris et al. (2007), but required participants to complete a GXT to exhaustion prior to sampling BDNF and testing executive function performance. Their results showed increases in serum BDNF levels coupled with enhanced performance on a working memory task following the GXT. Further support for increases in BDNF as a factor facilitating executive function performance has been provided by Winter et al. (2007). In that study, increases in BDNF were associated with enhanced performance on a vocabulary learning task following maximum intensity sprint intervals as well as after 40 minutes of moderate-intensity running, with the greatest performance changes observed in the interval exercise condition. Increases in serum BDNF levels were also found following a 30-minute bout of moderate-intensity aerobic exercise in a recent study by Tsai et al. (2014). However, in contrast to the previous findings, enhanced performance on a visuospatial attention task could not be directly attributed to BDNF. Taken together, a growing body of literature suggests serum BDNF levels increase following an acute bout of exercise and may be among the mechanisms that contribute to the relationship between exercise and executive function performance.

**Future Research Directions**

The current study provides novel findings demonstrating the beneficial effects of different intensities of exercise on executive function. Given the lack of evidence in this area and the potential for applying these findings to academic and workplace settings, further research is warranted. Moving forward, studies examining the relationship between an acute bout of exercise and executive functioning should attempt to investigate different durations and intensities of exercise. For example, exercise performed at higher intensities or as high-intensity intervals have received little attention to this point. As our society continues to place greater prioritization on health and performance optimization, the benefits of high-intensity exercise that can be performed in a brief bout may be a key factor in promoting physical and cognitive health for populations that struggle to exercise due to a lack of time (Godin et al., 1994). Investigation of the type, duration and intensity of exercise which elicits the greatest health and cognitive benefits deserves attention in future research.

Future studies should also examine additional modalities of exercise. Currently, most of the studies examining the exercise – cognition relationship have utilized aerobic cardiovascular exercise (e.g., cycling, running). However, expanded investigation of the effects that can be obtained from different modalities of exercise such as resistance training is warranted. Recent studies by Chang and colleagues (2009a, 2009b) have shown that resistance exercise leads to enhanced cognitive function, however, the protocols in those studies involved two sets of six upper body exercises, which may not approximate the exercise prescription suggested by American College of Sports Medicine (ACSM; 2010) that may be used for whole body strength, endurance, and hypertrophy as major muscle groups in the lower body were neglected. Further research that can substantiate these effects and the nature of the resistance exercise – cognitive performance relationship should also be helpful for developing theory or a better understanding of physiological mechanisms (e.g., BDNF) that may be common to aerobic exercise as well.

Future studies should also look to focus on cognitive tests assessing different indices of executive function in order to better describe and understand whether the acute effects of exercise on cognitive performance are universal or whether some executive function processes show different exercise-related effects than others. To this point in time, research has been somewhat diverse in terms of the executive function tests that have been utilized in exercise research (see Table 1), limiting our ability to consolidate current findings to determine effects on specific indices of executive function. Thus, there is a need for research to consistently employ cognitive tests that have demonstrated validity and reliability in assessing a range of executive processes. In doing so, we will garner a more complete understanding of the effects of exercise on the three basic executive functions as well as tests that involve a combination of functions.

Future research should also explore individual differences in executive function in concert with the effects of exercise. For example, it would be interesting to determine whether people who have better executive function show the same effects as those with lower baseline executive function scores. It may be that people who perform more poorly on executive function tests show greater performance enhancement with exercise. If this is the case, research in this area may help to identify internal mechanisms (e.g., BDNF) that may be under-regulated in some people and the potential for acute exercise to be assistive for them in the pursuit of important daily tasks that involve executive function performance.

**Implications**

The findings from the present study also have a number of practical applications that may have meaningful positive real-world implications. For example, numerous occupations (i.e. police, fire fighters, military, and paramedics) often require high levels of physical exertion while on the job as well as execution of a number of complex cognitive tasks that require quick planning and decision-making, demands on working memory and response inhibition. In such environments, it is clearly important that these professionals and those who supervise and train them understand how executive functions may be hindered or facilitated by different physical activity requirements. Accordingly, the present results suggest that being active on the job may help facilitate cognitive performance on the job as well.

The current study also provides further support for the benefits of exercise that may be applied in academic performance or learning environments such as schools. As physical activity has been found to have positive implications for concentration, memory and classroom behaviour (Trudeau & Shephard, 2008), the current findings are of particular importance as teachers often struggle with concentration deficits and reduced attention (Budde, Voelcker-Rehage, Pietraßyk-Kendziorra, Ribeiro, & Tidow, 2008). Findings showing that executive function performance can be improved following as little as 20 minutes of exercise even when performed at a low-intensity may be important for teachers and students to consider prior to studying, preparing coursework, or writing tests and examinations. It may be particularly relevant that the current findings suggest facilitative effects of exercise last as long as 38 minutes following 20 minutes of exercise.

**Strengths and Limitations**

The current study has a number of strengths and limitations that must be acknowledged and interpreted. Among the limitations of the study are the sample and sampling procedures. Specifically, the sample was highly homogenous as all participants were recruited from a post-secondary educational setting, were all young adults between the ages of 18 and 25, and were all healthy enough to perform 20 minutes of high-intensity exercise. Accordingly, our findings are limited in terms of generalization to other populations that possess these characteristics. Pre-experimental assessments of physical fitness also indicated the sample was comprised of participants with above-average fitness levels (e.g. Mean$VO_2max$ = 49.17) (ACSM, 2010). This characteristic limits generalizability of the findings to people with similar levels of physical fitness. Higher than average fitness levels in the sample should also be considered when interpreting the findings because fitness levels have been suggested to be a moderator of the exercise – cognitive performance relationship, with greater fitness being associated with enhanced cognitive performance (Chang et al., 2012).

Another limitation relates to the executive function tasks used in the study. As shown in Tables 5, 6 and 7, there was a ceiling effect for total errors for performance on the Stroop task as participants responded correctly on nearly all trials. Although the response speeds were slower for the incongruent Stroop trials, it was expected there would be more errors on those trials as well. This finding suggests that characteristics of the task (e.g., stimulus presentation duration; limited stimulus processing involving only 3 parameters) may have not challenged participants' executive function capabilities particularly well. Future research should modify this task (e.g., shorter presentation time; more variable response possibilities) in order to effectively draw upon participant's executive resources during task performance. As noted above, future studies should examine additional executive function tasks that assess indices of executive function not targeted in the current study in order to facilitate a greater understanding of the relationship between exercise and executive function.

An additional limitation to be accounted for relates to the selection of exercise intensities and the limited ability to test whether there may be a dose-response relationship between exercise and executive function performance. The doses for the high-intensity and moderate-intensity steady-state conditions were strategically designed to match the arousal and workload characteristics of the HIT exercise stimulus. As such, the exercise intensities did not follow a uniform linear, or graded pattern. While the current findings suggest that HIT may show a unique relationship with executive functioning it may have been insightful for this study to have examined linear increments in exercise intensity (e.g. 30%, 50%, 70% $W_{max}$) that may more clearly test for dose-response relationships. Recent evidence suggests studies that incorporate more incremental doses of exercise intensity may be better able to discern subtle variations in executive function that may be linked to exercise dosage (Brown & Bray, in press; Chang & Etnier, 2009b; Kamijo et al., 2004, Kamijo et al., 2009).

A final limitation that should be noted is that the present design did not utilize a no-exercise control condition. The light-intensity exercise condition was used in order to control for the subtle cognitive and motor demands of performing the stationary cycling task. However, as is clearly evident from Figure 2, participants in the light exercise condition showed heart rates that were significantly above resting levels throughout the cycling task and therefore do not represent a non-treatment control group. Despite its limitations, a no-exercise control group would have provided data to determine if there were any practice effects associated with the repeated exposure to the executive function tests that may have artificially enhanced the performance scores from pre-post testing. Although we cannot be certain that no practice effects occurred, it should be noted that the executive function performance effect did diminish from immediately following exercise to 30-minutes post-exercise in all the groups. Had there been a practice effect, it would be expected that executive function performance would have improved progressively over time with repeated exposure to the testing stimuli.

While a number of limitations in the current study deserve attention, a number of strengths should also be highlighted. For instance, the current body of literature in this area has focused primarily on moderate-intensity exercise, with few studies having investigated effects associated with low and high-intensity exercise. Thus a major strength of the current study is that it provides some evidence that furthers our knowledge surrounding both low and high-intensity exercise, as well as contributing to the limited body of research examining the effects of HIT on cognitive function.

Another strength of the present study is that it is among the few to have assessed the immediate as well as delayed effects of exercise on executive function. Consequently, results from the current study provide novel findings demonstrating the beneficial effects that may be derived from performing 20 minutes of exercise at a variety of intensities for up to 38 minutes into recovery.

An additional strength of the study relates to use of both the Stroop and stop-signal tasks to assess executive function performance. The stop-signal task was created with the goal of examining response inhibition in a laboratory setting (Lappin & Eriksen, 1966; Logan & Cowan, 1984; Vince, 1948), while the Stroop task involves multiple indices of executive functioning including response inhibition and selective attention in addition to information processing (Miyake et al., 2000; Pachana et al., 2004). Many of the previous studies to investigate acute effects of exercise on executive function have used only one task at either one point in time, or with one or two follow-up tests (e.g., Byun et al., 2014, Joyce et al., 2009; Yanagisawa et al., 2010). The present study provides evidence based on two robust tests of executive function performed at multiple time points following exercise.

**Conclusion**

In conclusion, the present study contributes to the limited literature investigating the immediate and delayed effects of different intensities of acute exercise on executive function. Twenty minutes of exercise, regardless of intensity not only improves executive function immediately following, but also provides sustained effects that last up to 38 minutes following cessation of exercise. These findings lend support to the RAH model

(Dietrich & Audriffen, 2011), suggesting hypofrontality does not play a significant role following cessation of exercise and that enhanced performance on higher-order cognitive tasks may be expected immediately following exercise. Future research should further investigate dose-response issues relating to acute effects of exercise on executive function performance as well as continue to examine the effects of HIT. Multidisciplinary efforts should be implemented in order to explore mechanisms that may account for the present findings and others showing positive effects of exercise on executive function performance.

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# APPENDIX A: STUDY MATERIALS

Consent Form
Baseline Checklist
Physical Activity Readiness Questionnaire
Ratings of Perceived Exertion Scale

**PARTICIPANT LETTER OF INFORMATION / CONSENT FORM**

**Title of Study:** The impact of high-intensity interval training on cognitive performance.

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**Overview**

You are being invited to participate in this research study because you are a healthy, regularly active male or female between the ages of 18 and 30. In order to decide whether or not you want to be part of this research study, you should understand what is involved and the potential risks and benefits. This form gives you detailed information about the research study, which will be discussed with you. Once you understand the study, you will be asked to sign this form if you wish to participate. Please take your time to make your decision. Feel free to discuss it with your friends, family or your family physician.

**Purpose of the Study**

The purpose of this study is to examine psychological factors involved in participating in exercise at different intensity levels.

**Study Procedures**

This study involves two lab visits including a graded exercise test (pedaling on the bicycle at an easy resistance level which then becomes progressively harder (like riding up a hill that gets progressively steeper) until it becomes too difficult to continue), a 20-minute session of light, moderate, intermittent or strenuous exercise, assessments of cognitive performance and completing some surveys and questionnaires throughout.

**Potential Risks and Discomforts**

There are potential risks and discomforts associated with the exercise testing procedures which are similar to those associated with any form of strenuous physical activity and beyond strenuous for the graded exercise test due to the participant exercising until volitional exhaustion for the test to be concluded. These include fatigue, nausea, vomiting, fainting, abnormal blood pressure, irregular heart rhythm, and in very rare instances, heart attack, stroke or death. Every effort will be made to minimize these potential risks by evaluation of preliminary information relating to your health and fitness and by careful observations during testing. If you feel physically uncomfortable or dizzy when exercising you should inform the experimenter and immediately stop exercising. We will monitor how you are feeling and obtain medical assistance if necessary. The cycling tasks will likely tire you for a short duration. You may worry about your performance in the cycling task, but please keep in mind that your numbers are kept confidential and will not be compared against anyone else's scores. We are merely asking for your best effort. Some muscle soreness or discomfort during or after the cycling test is possible, but we will demonstrate how to decrease any discomfort or soreness you may experience.

You may feel confused or frustrated when performing the cognitive tests. These feelings are normal. Nonetheless, you should feel free to stop doing the tests if you desire. The surveys we will ask you to complete include questions about how you are feeling emotionally at the time and how you feel about exercise. You should feel free to not answer any questions if they make you feel sensitive or uncomfortable at any time.

**Injury Protection/Coverage**

Financial compensation for such things as lost wages, disability or discomfort due to this type of injury is not routinely available. However, if you sign this consent form it does not mean that you waive any legal rights you may have under the law, nor does it mean that you are releasing the investigator(s), institution(s) and/or sponsor(s) from their legal and professional responsibilities. If the researchers learn of anything that may endanger your health or well-being by participating, or continuing to participate in the study, you will be notified immediately.

**Potential Benefits**

We cannot guarantee any personal benefits from your participation in this study. However, during your participation you may gain insight into your exercise preferences and may have a chance to do some exercise that you might consider doing in the future. The general public will potentially benefit by learning about different types of exercise and how doing exercise relates to people's cognitive test performance.

**Confidentiality**

Any information that is obtained from this study will remain confidential. Appropriate measures, consistent with McMaster University Research Ethics Board guidelines, will be taken to ensure privacy. The results from this study will be used for educational purposes and shared with the scientific community. However, all personal information will be removed from the data and your name will not be recorded on any of the study documents. The questionnaires and test results are completely private and will be kept in a locked filing cabinet in The Health and Exercise Laboratory for a period of approximately six years. If the results of the study are published, your name will not be used and information that discloses your identity will never be revealed. Upon completion of the study, you will have access to a summary of the findings from the group data if you desire.

**Participation and Withdrawal**
You can decide whether to take part in this study or not. If you volunteer for this study, you may withdraw or have your data removed from the study at any time during or following any of the testing sessions. You may also refuse to answer any questions you don't want to answer or stop performing any of the tests while remaining in the study. The investigators may also withdraw you from the study if circumstances arise which warrant doing so. We expect to present some of the study findings in March, 2014. We also expect to present the full study in June 2014. **In the case that a participant decides to withdraw, their data provided will be destroyed unless otherwise indicated**. Should you choose to withdraw at any time during the first study session you will be awarded 0.5 credits for that session (or $5 if you are not from Psych 1XX3). Should you choose to withdraw at any time during the second study session you will be awarded 1.5 credits for that session (or $15 if you are not from Psych 1XX3).

**Payment/Reimbursement**
Participants recruited through 'Sona' are provided the opportunity to participate as a research subject in an actual experiment in the Dept of Psychology, Neuroscience & Behaviour and earn two credits (0.5 credits for session 1 and 1.5 credits for session 2) towards their final exam. Participants recruited through email, posters and announcements will receive an honorarium of $20.00 ($5 for session 1 and $15 for session 2.) in order to compensate for their time and effort.

**Information About the Study Results**
This study should be completed by approximately by the end of June, 2014. If you would like a brief summary of the results, please leave your email contact information below.

**Questions About the Study**
If you have questions or require more information about the study now or later, please contact any of the investigators listed above. As well, if you would like a brief summary of the study results, please feel free to contact us.

This study has been reviewed by the McMaster University Research Ethics Board and received ethics clearance. If you have concerns or questions about your rights as a participant or about the way the study is conducted, please contact:

McMaster Research Ethics Secretariat
Telephone: (905) 525-9140 ext. 23142
c/o Office of Research Services

E-mail: ethicsoffice@mcmaster.ca

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**CONSENT**

I have read the information presented in the information letter thoroughly. I have had the opportunity to ask questions about my involvement in this study, and all of my questions have been answered to my satisfaction. I understand that if I agree to participate in this study, I may withdraw from the study at any time. I have been given a copy of this form. I agree to participate in the study.

_______________________________________
Name of Participant

_______________________________________ ____________________
Signature of Participant Date

**Consent form administered and explained in person by:**

_______________________________________
Name and title

_______________________________________ ____________________
Signature Date

**SIGNATURE OF INVESTIGATOR**

In my judgment, the participant is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent to participate in this study.

_______________________________________ ____________________
Signature of Investigator Date

- o *Yes, I would like to receive a summary of the study's results.*
  *Please send them to this email address:*

## Demographics

Age:_____ years

What is your year of study? _____

What is your program of study? ___________

Sex: Female ____ Male ____

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

# PAR-Q & YOU

**(A Questionnaire for People Aged 15 to 69)**

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

| YES | NO | | |
|---|---|---|---|
| ☐ | ☐ | 1. | **Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?** |
| ☐ | ☐ | 2. | **Do you feel pain in your chest when you do physical activity?** |
| ☐ | ☐ | 3. | **In the past month, have you had chest pain when you were not doing physical activity?** |
| ☐ | ☐ | 4. | **Do you lose your balance because of dizziness or do you ever lose consciousness?** |
| ☐ | ☐ | 5. | **Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?** |
| ☐ | ☐ | 6. | **Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?** |
| ☐ | ☐ | 7. | **Do you know of any other reason why you should not do physical activity?** |

**If you answered**

## YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

## NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

**DELAY BECOMING MUCH MORE ACTIVE:**

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

**PLEASE NOTE:** If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

**No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.**

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ____________________

SIGNATURE ____________________ DATE ____________________

SIGNATURE OF PARENT ____________________
or GUARDIAN (for participants under the age of majority) WITNESS ____________________

**Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.**

## RATINGS OF PERCEIVED PHYSICAL EXERTION (RPE)

| rating | description |
|---|---|
| 6 | NO EXERTION AT ALL |
| 7 | |
| | EXTREMELY LIGHT |
| 8 | |
| 9 | VERY LIGHT |
| 10 | |
| 11 | LIGHT |
| 12 | |
| 13 | SOMEWHAT HARD |
| 14 | |
| 15 | HARD (HEAVY) |
| 16 | |
| 17 | VERY HARD |
| 18 | |
| 19 | EXTREMELY HARD |
| 20 | MAXIMAL EXERTION |