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Sprint interval training improves oculomotor planning in high-fit individuals independent of exercise modality

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A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Kinesiology

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Abstract

A single-bout of aerobic and/or resistance training for durations as brief as 10-min improves executive function across a continuum of aerobically sustainable intensities. The goal of my thesis was to determine whether sprint interval training (SIT) elicits a post-exercise benefit in executive function in a corpus of high-fit individuals (i.e., varsity rowers). SIT sessions entailed 30 s “as hard as you can” efforts, interspersed by 90 s active recovery intervals (i.e., low resistance movement) for a duration of 10-min. Separate SIT sessions were completed via sport- (i.e., rowing ergometer) and non-sport-specific (i.e., cycle ergometer) modalities to determine if a putative SIT executive benefit is related to metabolic or intensity demands. Pre- and post-exercise executive control was measured via the antisaccade task. Pro- and antisaccade post-exercise RTs improved – a result that was independent of exercise modality. Accordingly, results suggest that SIT contributes to a post-exercise benefit in arousal.

Key Words

Executive Function

Sprint Interval Training

Antisaccades

Rowing Ergometer

Cycle Ergometer

Summary for Lay Audience

This study examined whether a session of sprint-interval training (SIT) produces an improvement to executive function. High-fit individuals were used in my study because the effect is not greatly seen in low-fit individuals. The exercise protocol consisted of 30 second 'as hard as you can go' efforts separated by 90 seconds of light exercise. The 30 second pieces were completed 5 times for a total of 10 minutes of exercise. The antisaccade task was performed before the exercise task and then immediately after once the participant's heart rate got below 100 beats per minute. There were two different exercise types. Each participant would complete the exercise task on a rowing ergometer and a cycling ergometer. I found that antisaccades produce longer reaction times than prosaccades which is consistent with other studies. I found a decrease in antisaccade reaction times from the pre-exercise antisaccade task to the post-exercise antisaccade task. I also found a decrease in post-exercise prosaccades. This suggests that after SIT, there is an increase in physiological arousal as well.

Co-Authorship

The author, under the supervision and mentorship of Dr. Matthew Heath, conducted this Master's thesis. With the guidance of Dr. Matthew Heath, I designed the experiment, collected, analyzed and interpreted data, and prepared this thesis document.

Acknowledgements

First and foremost, I would like to acknowledge my supervisor, Dr. Heath. Thank you for accepting me into your team and lab as a Masters candidate. It's been a long road, but I am thankful for your patience with me as well as your constant guidance. I am also thankful for the funding provided by UWO as well as Dr. Heath for allowing me to continue my education.

I would like to give a shout out to all my participants. Some of them pushed themselves to the limits for my research, adjusted their training schedule, and even had to visit a garbage can after their test.

I also would like to thank Western's Rowing Team, especially Dr. Daniel Bechard and Dr. Volker Nolte. Without them, I would not be here. They presented the opportunity to come train with them and win with them. Along with all my teammates, we became the first Canadian university to win the Head of the Charles, we won OUAs together, and won a few Canadian Henley medals. I believe that because of my coaches and teammates, we are the best lightweight team in North America. ESBU!

I would like to thank all my lab mates I have had throughout the years who have shown me the ropes and helped me along the way. To all my friends who were always there to support me especially my roommates who had the pleasure of living with me for all this time.

Lastly, my family, especially my parents Antony and Joanne. You both have helped me persevere through my Masters and all my other crazy dreams I have had along the way. I cannot express in words how much I love you! Also to my two brothers, James and Anthony, thank you for always being there for me.

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List of Terms and Abbreviations

BDNF-Brain-Derived Neurotrophic Factors

CV of RT-Coefficient of Variation of Reaction Time

HR_{max}- Maximum Heart Rate

SIT-Sprint Interval Training

LT-Lactate Threshold

MoCA-Montreal Cognitive Assessment

MT-Movement Time

PAR-Q-Physical Activity Readiness Questionnaire

RPE-Rating of Perceived Exertion

RT-Reaction Time

VO_{2peak}-Peak Oxygen Uptake

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Introduction

A growing body of literature has shown that long-term exercise improves brain health (Colcombe and Kramer, 2003). In particular, Colcombe and Kramer's meta-analysis reported that exercise benefits cognition across a broad range of ages and demonstrates the most reliable benefit for executive function. Executive function represents the ability to process and attend to single and multiple stimuli, update and monitor working memory, and assert high-level inhibitory control (Norman and Shallice, 1986). This executive benefit is also observed in older adults at risk for cognitive decline (Heath et al., 2016). The improved post-exercise executive function has been related to increased: (1) regional cerebral blood flow, (2) brain derived neurotrophic factor (BDNF)¹ (Dinoff et al., 2017) and (3) catecholamine concentration (Anish, 2005), (4) stimulation of neurogenesis via cell proliferation (van Praag et al., 1999), and (5) cortical density and connectivity (Colcombe et al., 2004; Ruscheweyh et al., 2011; Voss et al., 2010).

In addition to chronic exercise, research has shown that a single-bout of aerobic or resistance training improves executive function (Chang et al., 2012) – a finding neuroimaging and electrophysiology studies have attributed to enhanced activity in the same frontoparietal networks as associated with executive improvements following chronic exercise (Hiura et al., 2010). For example, Chang et al. reported that participants demonstrated improved Stroop Interference task performance following a 20-min single-bout session of resistance training (i.e., 2 sets of 10 repetitions (rep) (i.e., an assortment of weight training movements) at 75% of 1 rep

¹ Brain derived neurotrophic factor is a protein of the neurotrophin family that is required for neuron growth, survival, and differentiation. An increase in BDNF concentrations may result in an increase of neuronal growth, survival, and synaptogenesis and produce a post-exercise executive benefit (Dinoff et al., 2017).

maximum –right-arm and left-arm curl, dumbbell rowing left and right-hand, dumbbell lateral raise, and bench press). The Stroop Interference task entails responding to a word printed in ink that is either congruent (i.e. standard word-naming task) or incongruent (i.e., non-standard word-naming task) to the meaning of the written word (Stroop, 1935). Notably, the non-standard variant of the Stroop Interference task requires inhibiting a pre-potent response and is therefore held as an exemplar measure of executive function. Accordingly, Chang et al.’s finding demonstrates that exercise positively benefits executive function.

In addition to the nature of the cognitive process being evaluated, Chang et al.’s (2012) meta-analysis states that exercise duration and intensity are primary moderators of the single-bout exercise effect on executive function. In particular, Chang et al. reported that 20-min of exercise is necessary to elicit a reliable post-exercise benefit. It is, however, important to note that Johnson et al. (2016) reported that older adults (71.7 years of age) demonstrated improved Stroop Interference task performance following as little as 10 min of aerobic or resistance training. In their study, participants completed aerobic (via cycle ergometer) and resistance training for 10 or 30 min at a “somewhat hard” to “hard” intensity (i.e., Borg Rating of Perceived Exertion of 13 to 14)². Johnson et al. concluded that the improved executive function following as little as 10 min of exercise is associated with an increased cognitive reserve in older adults (Stern, 2009). In turn, Samani and Heath (2018) found that young healthy adults produced a post-exercise executive benefit following a 10-min single-bout of aerobic training at a moderate to vigorous intensity (i.e., 60-85% of HR_{max}). Therefore, a

² The Borg Rating of Perceived Exertion is a scale to measure one’s perceived exertion during exercise (Borg, 1982).

positive post-exercise benefit can be accrued in as little as 10 min and appears to extend the continuum of young and older (cognitively) healthy adults.

In terms of intensity, work involving young adults has shown that moderate to vigorous intensities produce the largest post-exercise benefit to executive function (for meta-analysis see Chang et al. 2012). For example, Brisswalter et al., (2002) reported that moderate to heavy exercise intensities (i.e., 40-80% VO_{2max}) elicit the largest magnitude improvement in post-exercise executive function, whereas McMorris and Hale (2012) reported that improved executive function is limited to intensities above 75% of VO_{2max} . It is, however, important to note that previous studies have generally employed absolute measures of intensity such as HR_{max} (i.e., Karvonen formula) and the percentage of VO_2 and therefore do not account for individual differences in performance. In an attempt to address this, work by my group (Heath et al. 2018) examined post-exercise executive function following 10-min of aerobic exercise (via cycle ergometer) at three metabolically distinct, and participant-specific, intensities: (1) 80% of lactate threshold (LT) (i.e., moderate intensity), (2) 15% of the difference between LT and VO_{2peak} (i.e., heavy intensity) and (3) 50% of the difference between LT and VO_{2peak} ³ (i.e., very-heavy intensity). Lactate threshold is the point between moderate and heavy intensities where oxygen uptake and blood lactate reach a steady state and exercise can maintain for an extended period of time (Ghosh, 2004). Results showed that the magnitude of the post-exercise executive benefit did not vary with exercise intensity. Further, this result was extended to cognitively healthy older adults (mean age=73 years, SD=6) (Petrella et al. 2019). Accordingly, a

³ VO_{2max} represents the plateau of maximum oxygen use and is determined via a confirmatory ride, whereas VO_{2peak} is derived from a single test (Whipp, 2010).

single-bout executive benefit can be accrued in as little as 10-min of exercise and is associated with a continuum of moderate to very-heavy intensities.

An important feature associated with my group's work (i.e., Heath et al. 2018) is that executive function was examined via pro- and antisaccade performance. A prosaccade is a stimulus-driven response requiring that an individual "look" to the veridical location of an exogenously cued target, whereas antisaccades require that an individual saccade mirror-symmetrical to a target. The benefit of pro- and antisaccade performance – when compared to other tasks such as the Stroop Interference – is that it is hands and language free and therefore provides a tool that is sensitive to subtle changes in executive function. A myriad of studies have shown that an antisaccade produces longer reaction times (RT), more directional errors, and less accurate and more variable endpoints (Hallett, 1978; Gillen and Heath, 2014) than their prosaccade counterparts. Neuroimaging and electrophysiological work involving humans and non-human primates has shown that the behavioural 'costs' associated with antisaccades reflects the two-component executive processes of suppressing a stimulus-driven prosaccade (i.e., response suppression) and the visual remapping of a target's coordinates in mirror-symmetrical space (i.e., vector inversion) (Munoz and Everling, 2004). Notably, the frontoparietal networks that mediate antisaccades are the same networks that have been shown to demonstrate improved task-dependent activity following single-bout (Hiura et al., 2010; Seifert and Secher, 2011) and long-term (Colcombe et al., 2004; Voss et al., 2010) exercise. Accordingly, the temporal precision of eye-tracking (i.e., 1000 Hz in the present thesis) and the known neuroanatomical correlates of the antisaccade task makes it an ideal tool for examining post-exercise changes to executive function. Further, pairing prosaccade

performance with antisaccades provides a natural control for examining whether post-exercise changes in performance are executive-specific or entail a general improvement in oculomotor control (e.g., improved arousal).

The goal of the present thesis was to examine whether Sprint interval training (SIT) results in a post-exercise executive benefit and to determine whether the modality of SIT training influences the magnitude of the putative post-exercise benefit. High-intensity-interval training (HIIT) is characterized by relatively short bursts of vigorous exercise separated by periods of rest or low-intensity exercise for recovery (Gibala et al., 2013). In my current study we are using a variation of HIIT known as SIT. The difference between the two interventions is that SIT uses 'as hard as you can go' sprint efforts while HIIT uses different zones based on the participant's individual fitness (i.e. 90-95% HR_{max}) to determine the work rate to complete the HIIT protocol (Naves et al., 2018). Naves et al. found that HIIT and SIT both increased cardiorespiratory fitness and concluded that both tests are viable, but the advantage of SIT is that it does not need complex tests to define the intensity of the exercise. To my knowledge only six studies have examined whether HIIT training influences a post-exercise executive benefit. For example, Coetsee and Terblanche (2017) had older adults (55-75 years old) complete HIIT (i.e., 4 sets of 4 min treadmill walking at 90-95% HR_{max}, interspersed by 3 min active recovery at 70% HR_{max}), as well as resistance training (i.e., 3 sets of 10 repetitions at 50%, 75%, and 100% of individual's 10 rep maximum), and moderate continuous aerobic training (i.e., 47 min of continuous treadmill walking at 70-75% HR_{max}). Coetsee and Terblanche measured reaction time and accuracy for each trial of the Stroop Neutral task (i.e., identify the colour of a rectangle with the choices written in black- the colour subtask) and the Stroop Incongruent task

(i.e., identify the ink colour of a word written in incongruent coloured ink- the incongruent colour-word subtask). Stroop Interference was calculated by subtracting the RT from the Neutral task with the RT from the Incongruent task. Results from the Stroop Interference task showed that aerobic and resistance training had the greatest executive function (i.e., the incongruent colour-word subtask of the Stroop Incongruent Task), whereas the HIIT condition had the greatest improvement on information processing speed (i.e., by the colour-word subtask of the Stroop Neutral Task) (Coetsee and Terblanche, 2017). In contrast, a study in overweight adults found that HIIT (i.e., 4 bouts of 4min at 85-95% HR_{max} , interspersed by 4 min of active recovery at 75-85% HR_{max}) does not positively impact cognitive performance as measured via the Montreal Cognitive Assessment (MoCA) tool (Quintero et al., 2018). The authors concluded that such a result indicates that the physiological and psychological demands of HIIT training does not extend to a post-exercise executive benefit to low-to-average-fit individuals. The former study showed that there is a possible reduction of executive function after HIIT and more work needs to be done to find a benefit. In particular, the authors concluded that high-fit individuals must be explored in future work to examine a putative post-exercise executive benefit following HIIT training. I would, however, like to note that the MoCA is a clinical tool used to evaluate global changes in cognitive performance (Nasreddine et al., 2005) and therefore may not provide the requisite resolution to detect post-exercise changes in executive function.

The goal of my study was to examine a putative SIT-based post-exercise executive benefit in high-fit individuals (i.e., varsity rowers). Rowers were selected because they represent a corpus with some of the highest cardiorespiratory performance variables compared

to other endurance athletes (i.e., swimmers and runners) (Sousa et al., 2018). Accordingly, the selection of varsity rowers ensured a sample of high-fit individuals. Participants completed their SIT training on a rowing ergometer and a cycle ergometer. The basis for including rowing and cycle ergometers was that rowing is associated with increased cardiac output when compared to cycling (Horn et al., 2015) and therefore may contribute to increased regional cerebral blood flow due to the increased cardiorespiratory demands, higher lactate production, and higher HR_{max} – factors that are thought to indirectly contribute to enhanced executive function (Chang et al., 2012). For rowing and cycling ergometers the SIT protocol consisted of 5 sets of 30 s ‘as hard as you can go’ efforts, interspersed by 90 s of active recovery. To assess for post-exercise changes in executive function, I examined pre- and post-exercise pro- and antisaccade performance. In terms of research predictions, if rowing elicits the largest decrease in post-exercise antisaccade RTs then results would suggest that an executive benefit is correlated with exercise modality. In contrast, if the magnitude of the post-exercise benefit to RT is equivalent for rowing and cycle ergometers, the post-exercise executive benefit is independent of exercise modality. This study will provide a framework for determining whether an executive benefit is dependent on the exercise modality.

Methods

Participants

Fifteen participants (8 males, 7 females; age range = 18-24 years of age) from the University of Western Ontario Varsity Rowing Team volunteered to participate in this research. Participants had normal or corrected-to-normal vision and no pre-existing neurological

disorders. All participants achieved a full score on the Physical Activity Readiness Questionnaire (PAR-Q) and were instructed to refrain from caffeine and alcohol, rigorous exercise for twelve hours before each exercise session, and to get a full eight hours of sleep the night before. Participants provided informed written consent approved by the Health Sciences Research Ethics Board, University of Western Ontario, and this experiment was conducted according to the Declaration of Helsinki.

Exercise Protocol

Participants performed their sprint interval training (SIT) sessions on a cycle (Monark 818E Ergomedic Cycling Ergometer, Vansbro, Sweden) and a rowing (Concept 2 Model D Rowing Ergometer, Morrisville, Vermont, USA) ergometers. A Polar Heart Rate monitor (Polar Wearlink+ Coded Transmitter, Polar Electro Inc., Lake Success, NY, USA) was used to track their heart rate during and after exercise. Prior to the onset of an exercise session participants completed 2 min of stretching and then completed 5 min of low-intensity (i.e., HR<150bpm) cycling or rowing. Following the warm-up, participants completed a 10-min cycling or rowing SIT protocol. The protocol consisted of five, 30 s bouts of “as hard as you can go” effort, followed by 90 s of light spinning or rowing. Participants self-selected the cycling and rowing resistance for their individual SIT protocols. For the cycling and rowing sessions, participants began their first 30 s bout of “as hard as you can go effort” in a stop position. More specifically, for both the cycle and rowing ergometers this meant that the flywheel was completely stopped and not moving. Strong verbal encouragement was provided during each 30 s SIT interval. The cycle and rowing ergometer sessions were randomly ordered and separated by at least 24 hours. They also reported their one stroke peak power test (i.e., the largest wattage produced

on one stroke, over the series of 10 strokes) completed two weeks prior to the end of their competitive season and between 1-4 weeks before they begin this study.

Oculomotor Task

Prior to and after the cycling and rowing ergometer session, participants completed an oculomotor assessment. For each assessment, participants sat in a height-adjustable chair in front of a tabletop (height 775 mm) with their head placed in a head-chin rest. A 30-in. LCD monitor (60 Hz, 8 ms response rate, 1280 by 960 pixels; Dell 3007WFP, Round Rock, TX, USA) was placed at participants' midline and 550 mm away from the edge of the table and was used to present visual stimuli. The gaze location of participants' left eye was measured via a video-based eye-tracking system (EyeLink 1000, SR Research Ltd., Mississauga, Ontario, Canada) sampling at 1000 Hz. Two additional monitors – visible only to the experimenter – provided the experimenter with real-time point of gaze information, trial-by-trial saccade kinematics (e.g. displacement, velocity), and information related to the accuracy of the eye tracking system (i.e., to perform a calibration and recalibration when necessary). Computer events and the presentation of visual stimuli were controlled via MATLAB (7.6: The MathWorks, Natick, MA, USA) and the Psychophysics Toolbox extensions (ver 3.0; Brainard, 1997). The lights in the experimental suite were dimmed during data collection and a nine-point calibration of the viewing space was completed prior to data collection.

Visual stimuli were presented on a high-contrast black background and included a green or a red fixation cross (each cross was 1°) located at the centre of the monitor and at the eye level of the participant. Target stimuli were white circles (2.7°: 135 cd/m² [Candela per square

meter, unit of luminous intensity]) located 10.5° (i.e., proximal target) or 15.5° (i.e., distal target) to left and right of the fixation cross and in the same horizontal axis. The start of each trial began with onset of the fixation cross which instructed participants to direct their gaze to its location. Once a constant gaze was achieved ($\pm 1.5^\circ$ for 500ms), a randomized fore period was initiated (i.e., 1000–2000ms) after which the fixation cross was extinguished and a 200 ms gap was introduced prior to the presentation of the target (i.e., gap paradigm). A gap paradigm was employed because it has been shown to produce more antisaccade directional errors than its overlap counterpart (i.e., fixation and target simultaneously extinguished) (Munoz and Everling, 2004). Following the 200 ms gap interval, a target was presented (i.e., 50 ms) and participants completed their instructed pro- or antisaccade following its onset. The green fixation cross cued participants to prosaccade (i.e., saccade to the veridical target location), whereas the red fixation cross cued an antisaccade (i.e., saccade mirror-symmetrical to the target stimulus). The brief target presentation was used to equate extraretinal feedback across pro- and antisaccades (Heath et al. 2011).

Pro- and antisaccades were completed in separate and randomly ordered blocks at each pre- and post-exercise oculomotor assessment. For each block 20 trials were completed to each target location (i.e., left and right of fixation) and eccentricity (i.e., proximal and distal) combination. Target location and eccentricity were randomized within a block. Following the pre-exercise oculomotor assessment participants immediately began their prescribed SIT exercise intervention. The post-intervention oculomotor assessment occurred only when the participant's heart rate was less than 100 bpm and this ranged from 5 to 10 min post-exercise. Once this was achieved, participants began their post-exercise oculomotor assessment.

Oculomotor data reduction, dependent variables, and statistical analyses

Oculomotor data were filtered offline via a dual-pass Butterworth filter, with a low-pass cut-off frequency of 15 Hz. A five-point central-finite difference algorithm was used to compute acceleration and instantaneous velocities. Saccade onset was determined by velocity and acceleration values of greater than $30^\circ/s$ and $8,000^\circ/s^2$, respectively. Saccade offset occurred when velocity values were less than $30^\circ/s$ for 15 consecutive samples (i.e., 42 ms).

Dependent variables for the oculomotor task were reaction time (RT: time from target onset to saccade onset), the coefficient of variation (CV) of RT (standard deviation/mean \times 100%), percentage of directional errors (i.e., prosaccade instead of an instructed antisaccade, or vice versa), movement time (MT: time from movement onset to movement offset) and saccade gain (i.e., saccade amplitude/veridical target location) in the primary (i.e., horizontal) movement direction. Dependent variables were examined via 2 (time: pre-exercise, post-exercise) by 2 (task: prosaccade, antisaccade) by 2 (exercise-type: rowing, cycling) fully repeated measures analysis of variance (ANOVA). Trials involving an express saccade (i.e., $RT < 65ms$), and amplitude less than 2° or greater than 2.5 standard deviations above participant- and target-specific mean were excluded from data analysis. Less than 14% of trials for any participant were removed due to the criteria listed above.

Results

Figure 1 shows pro- and antisaccade RT frequency histograms for each exercise-type at pre- and post-exercise assessments. The histograms demonstrate the expected finding that

antisaccades produced longer RTs than prosaccades. Further, the histograms indicate that the frequency of short-latency pro- or antisaccades did not differ across exercise-type or time – a finding indicating equivalent pre-saccadic movement processes across pre- and post-exercise assessments. Quantitative analyses of RT produced main effects of time, $F(1,14) = 11.74$, $p = .004$, $\eta_p^2 = 0.46$, and task, $F(1,14) = 87.81$, $p < .001$, $\eta_p^2 = 0.86$. RTs for antisaccades (254ms, $SD=32$) were longer than prosaccades (173 ms, $SD=21$) and were longer in the pre- (220ms, $SD=24$) than post-exercise assessment (207 ms, $SD=20$) (Figure 2). Notably, and in light of the primary goal of this study, it is important to note that exercise-type as well as all higher-order interactions involving this variable were not significant (all $F(1,14) < 1.0$, $ps > .39$, $\eta_p^2 < .05$).

The CV of RT yielded main effects for task, $F(1,14) = 5.72$, $p = .031$, $\eta_p^2 = .29$, and its interaction with time, $F(1,14) = 4.98$, $p = .043$, $\eta_p^2 = .26$. Prosaccade pre-exercise ($M=50$, $SD=13$) did not differ from its post-exercise counterpart ($M=49,SD=11$) ($t(14) = .291$, $p = .776$), and antisaccade pre-exercise ($M=45,SD=12$) did not differ from its post-exercise ($M=49,SD=11$) counterpart ($t(14) = 1.23$, $p = .239$). Moreover, the CV of RT did not produce a main effect of exercise-type nor any higher-order interactions involving this variable, all $F(1,14) < 0.58$, $p > .46$, $\eta_p^2 < .04$.

There was a low percentage of directional errors across all participants for each exercise-type, and time of assessment manipulation. Of the absolute number of trials, 516 were directional errors (5%). Of the directional errors, 74 occurred during prosaccade (14% of all directional error trials), whereas 442 occurred during antisaccade trials (85% of all directional error trials). Because not all participants completed a pro- or antisaccade directional error

across each exercise-type and time of assessment, I did not subject directional error data to an inferential statistic.

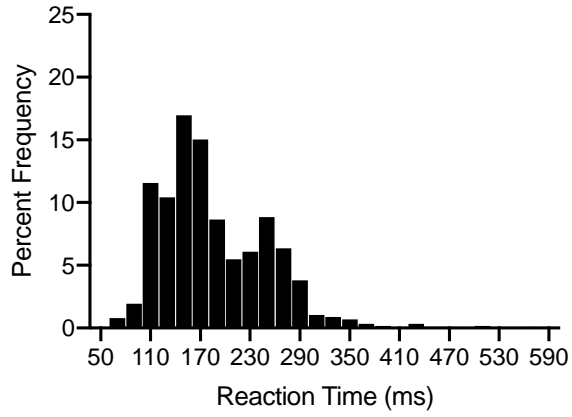
MT did not produce any significant main effects or interactions (all, $F(1,14) < 3.04$, $p > 0.1$, all $\eta_p^2 = 0.18$). Results for saccade gain (saccade endpoint/veridical location) produced a main effects for task, $F(1,14) = 6.11$, $p = 0.27$, $\eta_p^2 = 0.31$, and for time, $F(1,14) = 6.71$, $p = .021$, $\eta_p^2 = 0.32$. Gains were larger for pro- ($M=0.92$, $SD=0.64$) than antisaccades ($M=0.83$, $SD=.15$) and for pre-exercise ($M=0.91$, $SD=0.08$) compared to post-exercise ($M=0.86$, $SD=0.103$) (Figure 3).

As part of the rower's regular training, they had completed a one stroke peak power test on the rowing ergometer (i.e. the peak wattage produced on one stroke over a series of 10 consecutive strokes). Accordingly, I correlated each participant's peak power test with their antisaccade RT difference score (i.e., pre-exercise minus post exercise) for each of the rowing and cycling sessions. The basis for these analyses was to determine whether anaerobic power is related to a post-exercise benefit in executive function. Results showed that peak power and antisaccade RT difference scores were not reliably related across the cycle ($r=0.04$, $p=.86$) and rowing ergometer sessions ($r=0.26$, $p=.34$) (Figure 4). Notably, I do not have peak power data for the cycle ergometer.

Prosaccade

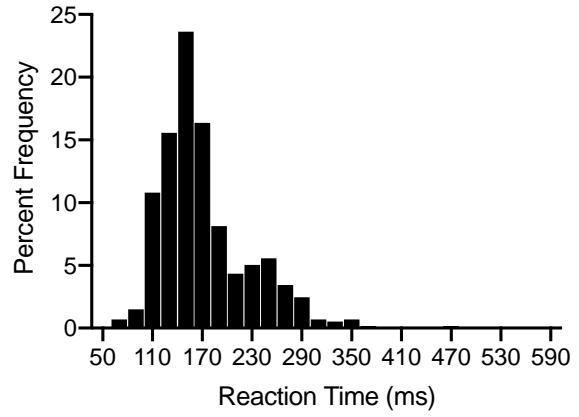
Rowing Ergometer

Pre-Exercise

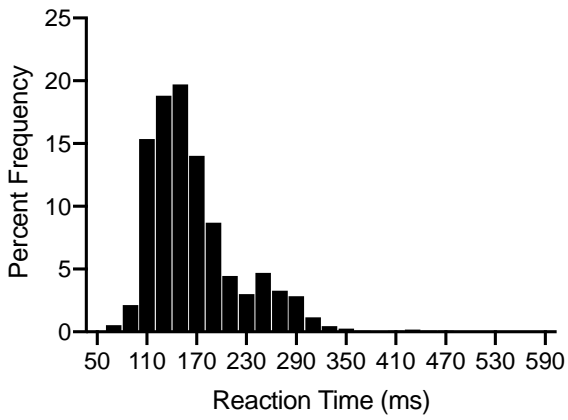


Cycle Ergometer

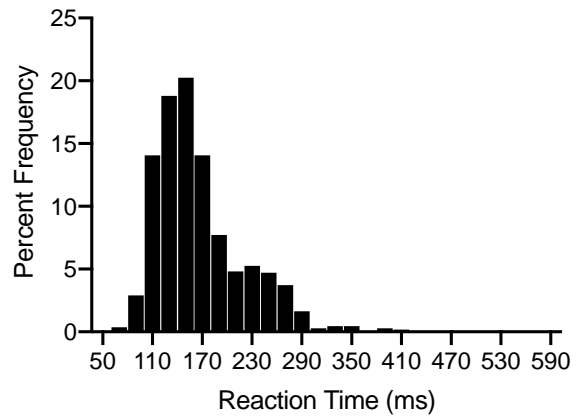
Pre-Exercise



Post-Exercise



Post-Exercise



Antisaccade

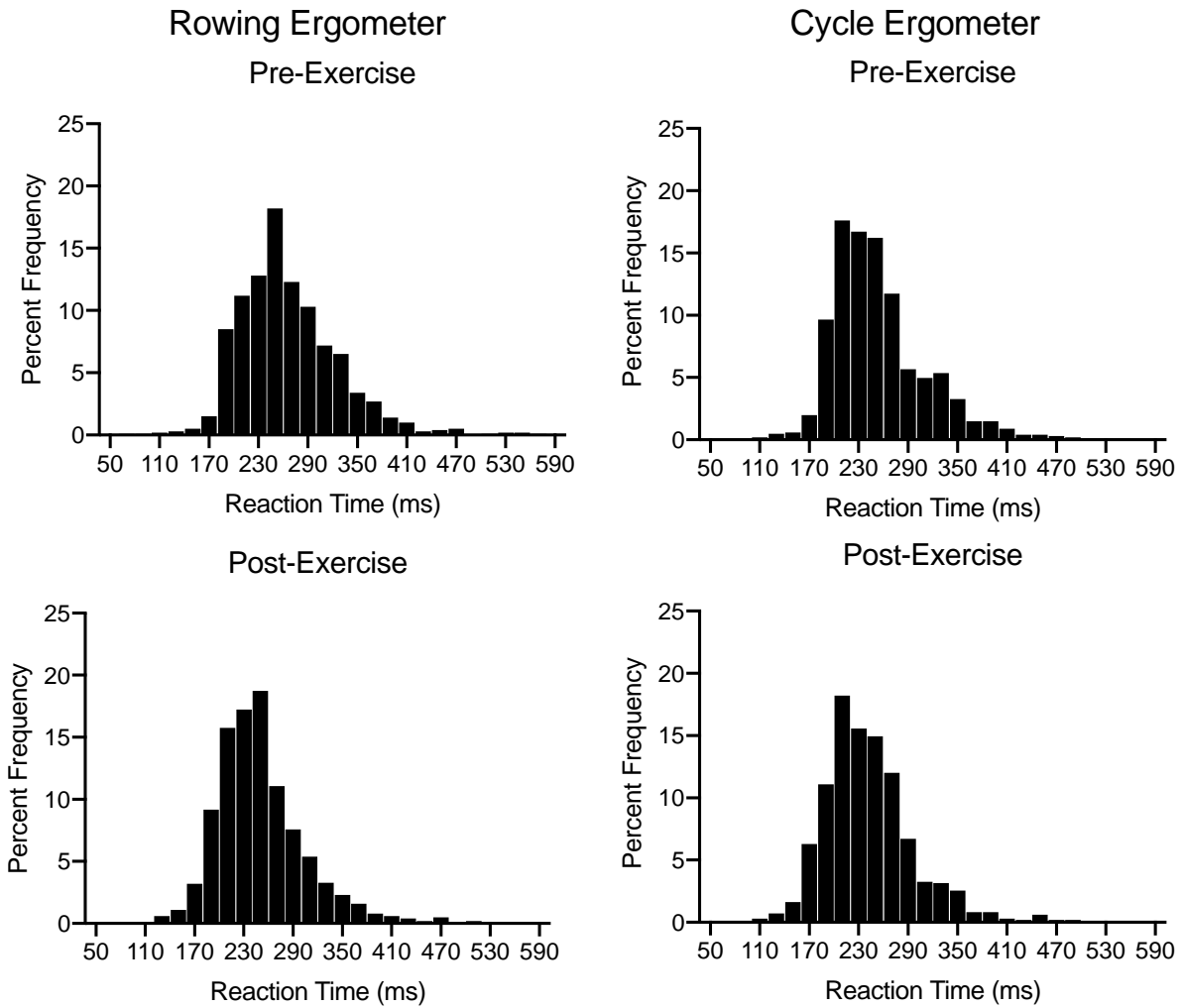


Fig. 1. Percent frequency histograms for pro- and antisaccades reaction times (ms) at pre- and post-exercise assessments for the rowing and cycle ergometer interventions. Bin widths are 60 ms increments.

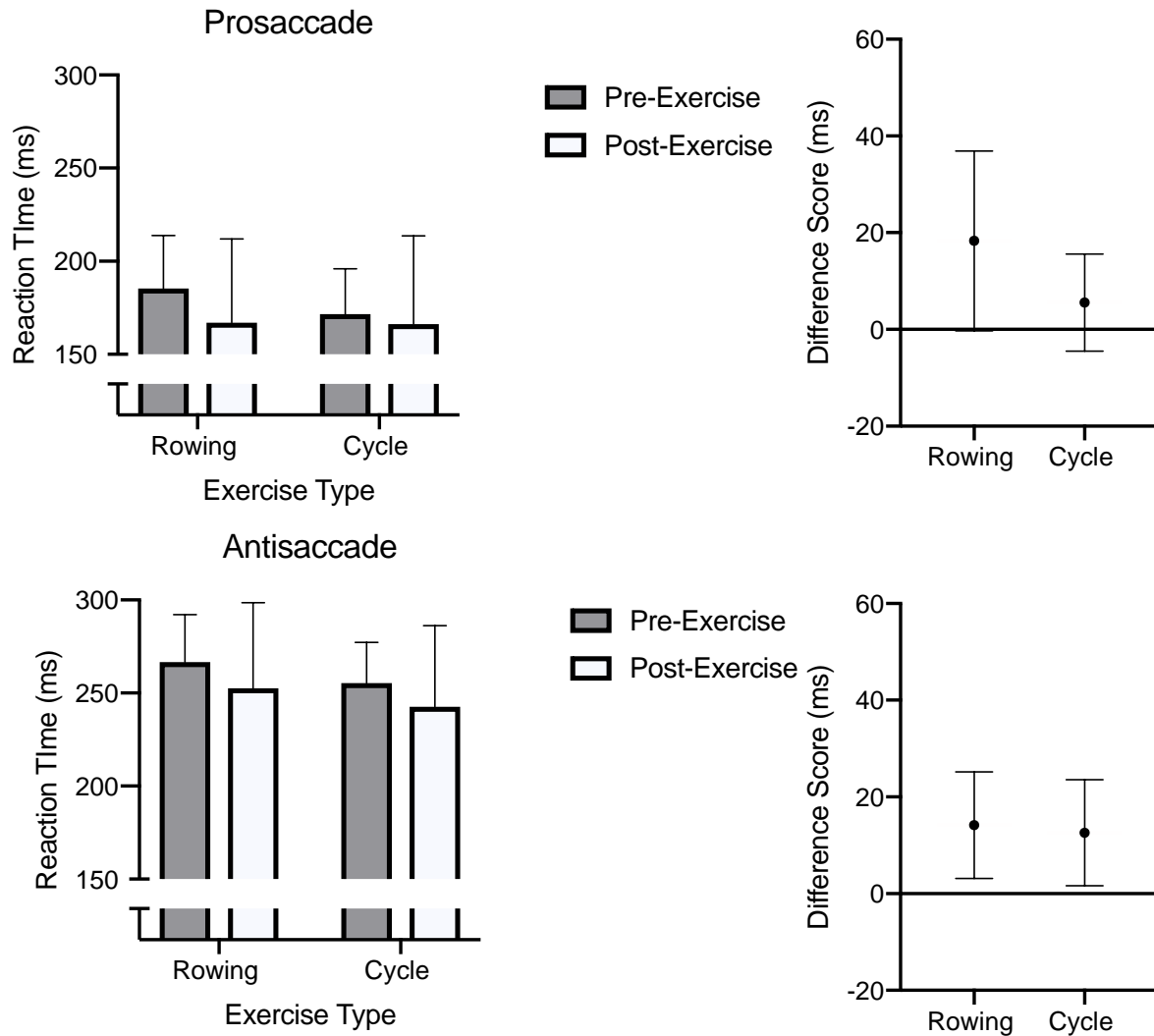


Fig. 2. The panels on the left show group mean pro- and antisaccade reaction times (ms) as a function of exercise-type and time of assessment. Error bars represent 95% of within-participant confidence interval. The right panels show mean pro- and antisaccade RT difference scores (pre-exercise minus post-exercise) for each exercise type. Error bars represents 95% between-participant confidence intervals.

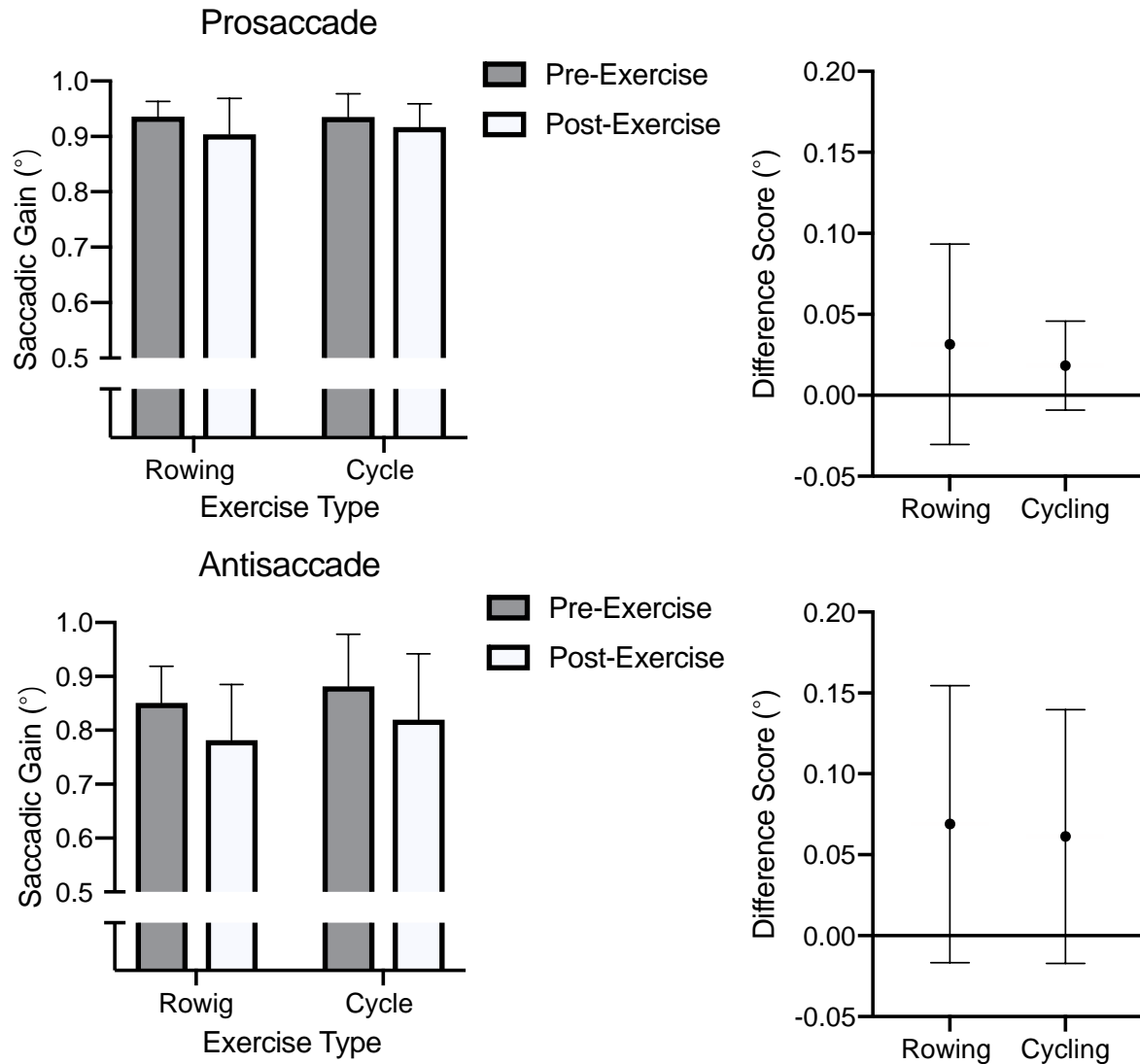


Fig. 3. Group means of pro- and antisaccade saccadic gain ($^{\circ}$) as a function of exercise-type and time of assessment. Error bars represent 95% within-participant confidence intervals. The right panels show mean pro- and antisaccade gain difference scores (pre-exercise minus post-exercise) for each exercise type. Error bars represents 95% between-participant confidence intervals.

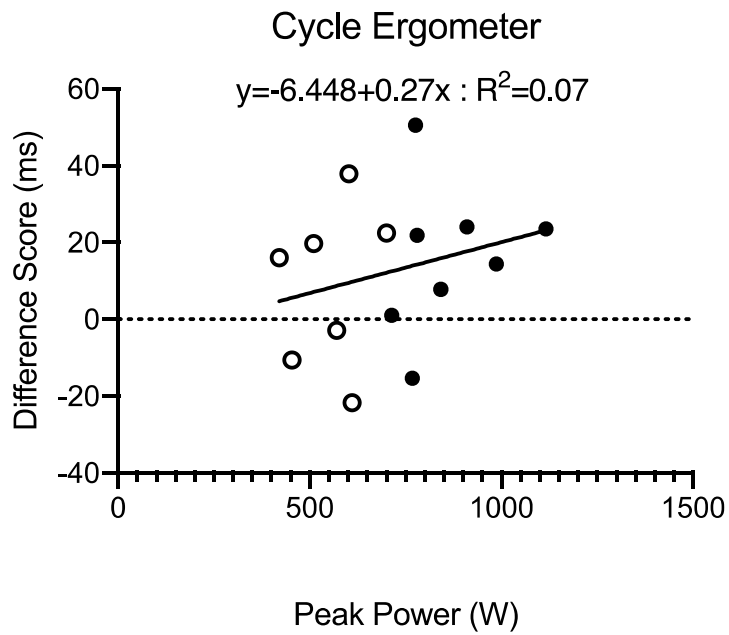
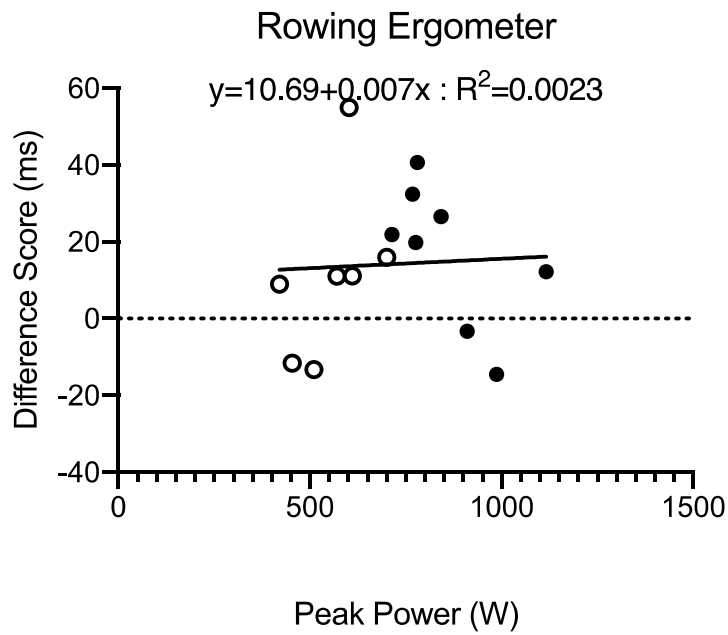


Fig. 4. Scatter plot of participants' max watts on the rowing ergometer as a function of their antisaccade RT difference score (pre-exercise minus post-exercise) on the rowing (top) and

cycle (bottom) ergometers. Closed and open data points represent male and female participants, respectively.

Table 1. Number of trials used in the analysis with directional errors in parentheses for each individual participant across all exercises.

Participant	Prosaccade				Antisaccade			
	Rowing		Cycle		Rowing		Cycle	
	Pre-exercise	Post-exercise	Pre-exercise	Post-exercise	Pre-exercise	Post-exercise	Pre-exercise	Post-exercise
1	78(1)	80(0)	80(0)	79(0)	71(1)	74(1)	74(6)	77(1)
2	76(1)	73(1)	79(1)	71(6)	57(5)	43(9)	41(10)	66(13)
3	78(0)	78(0)	75(1)	73(3)	78(1)	73(2)	77(3)	79(1)
4	79(0)	77(1)	77(1)	73(2)	74(5)	61(18)	64(14)	68(8)
5	67(7)	73(2)	76(3)	78(0)	75(5)	73(7)	75(3)	77(3)
6	79(0)	79(1)	80(0)	78(1)	73(6)	78(2)	78(2)	72(8)
7	74(1)	77(1)	78(0)	77(1)	67(2)	56(6)	69(6)	73(2)
8	68(2)	77(0)	69(1)	72(1)	66(15)	65(14)	65(14)	63(15)
9	78(1)	66(2)	78(1)	73(0)	73(5)	60(8)	70(4)	42(12)
10	78(0)	77(1)	73(0)	69(0)	57(9)	79(1)	78(0)	41(7)
11	71(0)	75(0)	73(0)	70(1)	71(9)	67(13)	67(11)	70(10)
12	78(0)	74(0)	71(3)	80(0)	74(4)	69(6)	74(4)	72(5)
13	72(3)	62(6)	74(2)	72(2)	51(3)	68(3)	65(4)	64(3)
14	79(0)	78(0)	68(1)	59(10)	41(26)	63(17)	36(25)	47(24)
15	76(1)	80(0)	79(0)	79(1)	74(6)	77(2)	72(8)	73(6)

Discussion

The goal of my study was to determine whether a SIT session involving high-fit individuals (i.e., varsity rowers) elicits a post-exercise benefit in executive function and determine whether the magnitude of this benefit is influenced by the training modality. In discussing my findings, I first outline the general differences between pro- and antisaccades before discussing the SIT influence on oculomotor performance.

Pro- and antisaccade RT, directional errors, and gain

Prosaccades had shorter RTs and produced fewer directional errors than antisaccades. The shorter RTs associated with prosaccades is consistent with work showing that responses with direct stimulus-response mapping are mediated via direct retinotopic projections to the superior colliculus (SC) that operate with minimal top-down executive – and hence cortical – control (Pierrot-Deseilligny et al., 1995). In turn, the longer RTs of antisaccades indicates further evidence that the executive demands of response suppression and vector inversion are a time-consuming and measurable process (Munoz and Everling, 2004). In terms of saccade gain, the fact that prosaccade gains approached – but did not attain – unitary is in line with the well-reported contention that prosaccades undershoot target location to minimize energy expenditure and/or saccadic flight time (Harris, 1995). Further, that prosaccades had larger gains than antisaccades supports the contention that the former are mediated via absolute retinotopic SC projections (Pierrot-Deseilligny et al., 1995), whereas the smaller gains associated with antisaccades indicate that the executive nature of such actions render motor output supported via visual pathways (i.e., relative) is functionally distinct from prosaccades (Gillen and Heath 2014; Heath et al. 2015). Importantly, the observed differences between pro-

and antisaccades recorded here provide a framework for examining exercise-mediated effects for a non-executive (i.e., prosaccade) and executive (i.e., antisaccade) task.

Pre- and post-exercise performance

Post-exercise antisaccade RTs were shorter than their pre-exercise counterparts – a finding consistent with previous work involving a single-bout of exercise (Heath et al., 2018; Samani and Heath, 2018). Furthermore, Samani and Heath showed that the benefit was not related to a practice-related effect as the decrease in RT was attributed to an exercise manipulation but not a non-exercise manipulation wherein participants sat and read a magazine for 10-min (i.e., control condition) between their pre- and post-oculomotor assessments. Further, the current results show that the post-exercise reduction is unrelated to a speed-accuracy trade off (Fitts, 1954) given that directional errors and saccade gains did not vary from pre- to post-exercise assessments. In other words, participants did not have shorter post-exercise antisaccade RTs at the cost of increased planning and control errors (see also Heath et al., 2018; Petrella et al., 2019; Samani et al., 2018).

In terms of a mechanism for the post-exercise antisaccade RT benefit, one favoured explanation is that exercise leads to an increase in BDNF concentration. BDNF is thought to increase neuronal growth and survival and promote synaptogenesis (Dinoff et al., 2017). In addition, it has been proposed that the increase in cerebral blood flow associated with exercise (Ogoh and Ainslie, 2009) may lead to improved efficiency of executive networks (Chang et al., 2012).

An unexpected finding in the current study was that prosaccades demonstrated a post-exercise RT reduction. This result counters a number of studies by my group showing that

single-bout (Samani and Heath 2018; Heath et al., 2018; Petrella et al., 2019) and chronic (Heath et al. 2016; 2017) exercise do not influence prosaccade planning times. The basis for the null prosaccade findings reported in my group's previous work is that such actions are mediated largely via direct retinotopic projection to the superior colliculus (Pierrot-Deseilligny et al., 1995) – a region that has not been traditionally associated with an exercise-related modification in neural activity (Colcombe et al., 2004). In reconciling these findings, it is important to note that the current work employed a SIT protocol and included only high-fit individuals, whereas previous work involved constant load aerobic exercise in a continuum of low- and high-fit individuals.

A possible reason that SIT may improve post-exercise pro- and antisaccade RTs is that the protocol results in a significant increase in catecholamine concentration and thus provides a general enhancement in physiological and psychological arousal. Indeed, the reticular-activating hypofrontality (RAH) theory states that exercise can lead to increased activity of the reticular formation which serves to energize and sustain physical motion and activate cortical regions that effect sensory attentional, and motor processes (Dietrich and Audiffren, 2011). Lehmann et al., (1985) reported a 50% lactate increase, 156% noradrenaline increase, and 165% adrenaline increase after incremental treadmill tests (i.e., 8km/h running and increased by 2km/h every 3min until exhaustion) at submaximal-maximal workloads. The blood lactate and catecholamine increase was also reported by Dietrich and Audiffren in their RAH hypothesis. The increase in catecholamine levels is one of the primary mechanisms for enhanced physiological and psychological arousal and provides the framework for the decrease in prosaccade RTs associated with SIT.

Exercise-type not a factor in post-exercise RT differences

My thesis also contrasted pre- and post-exercise oculomotor control across two distinct modalities: rowing and cycling ergometers. The basis for the comparison was to determine if the type of exercise modality produces a different magnitude post-exercise benefit. Indeed, recall that evidence has shown that the rowing ergometer is associated with greater metabolic demands (e.g., increased cardiac output and stroke volume) than the cycle ergometer (Horn et al., 2015). My results showed that the post-exercise benefit in oculomotor control was the same across both modalities. Thus, a conclusion to be made is that a post-exercise benefit to oculomotor control is independent of metabolic costs and/or intensity demands (see also Heath et al. 2018; Petrella et al. 2019).

The present work did not employ a VO_{2max} test and thus is not able to determine individual participants' cardiorespiratory fitness. In lieu of this, participants were asked to self-report their peak power in watts on the rowing ergometer. Notably, for varsity rowers, peak power is a known variable and reflects the highest wattage attained across 10 strokes, as hard as they can go (Nolte, 2011). Accordingly, I used peak power as a basic proxy for 'fitness' and correlated that measure with participants' post-exercise antisaccade RT benefit (i.e., pre- minus post-exercise) to determine if fitness level was related to improved post-exercise oculomotor performance. Results showed that the measure were not related and is consistent with some recent work reporting that fitness level does not influence the degree to which participants experience a post-exercise benefit to cognitive performance (Ludyga et al., 2016).

Study limitations and future directions

Extension of the present findings to the general population are constrained by several methodological traits. First, I employed only high-fit individuals without a comparison group of low-fit individuals. Accordingly, it is unknown whether the SIT post-exercise oculomotor benefit observed here is specific to high-fit individuals or can be extended to the continuum of fitness levels. Second, the duration between the end of an exercise session and the onset of the post-exercise oculomotor assessment was based on participants' having a heart rate less than 100 bpm, and this time frame was different for each individual. Because the post-exercise oculomotor assessment would begin at different times for each individual rather than a controlled time for each participant could give different post-exercise results based on the amount of rest each participant received. Third, it is unclear how long the post-exercise benefit to oculomotor control might persist given that only a single time point was used to assess a post-exercise benefit. Future work might consider a range of time points (i.e., immediately, <20 min, 30 min, 60 min) to examine the temporal durability to the post-exercise benefit in oculomotor control. Fourth, the low-resistance, 90 s, intervals between the 30 s of SIT may have contributed to the post-exercise benefit in oculomotor control. Accordingly, future work should have participants rest during the intervals between the sprint training. Such a methodology would help determine whether an exercise benefit relates to sprint-interval training or the low intensities exercise sessions.

Conclusions

The present study demonstrates that high-fit individuals who complete a 10-min session of SIT training on rowing and cycling ergometers exhibit a benefit in oculomotor (i.e., pro- and antisaccade) planning. The fact that the benefit was associated with pro- *and* antisaccades indicate that SIT training in high-fit individuals provides a general boost to physiological and psychological arousal.

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Appendices

Appendix A: Approval notice from the Office of Research Ethics, The University of Western Ontario



Date: 18 July 2018

To: Dr. Matthew Heath

Project ID: 111443

Study Title: Cognitive Differences Between Rowers and Non-rowers using the Antisaccade Task after High Intensity Interval Training

Application Type: HSREB Initial Application

Review Type: Delegated

Full Board Reporting Date: 07Aug2018

Date Approval Issued: 18/Jul/2018 15:14

REB Approval Expiry Date: 18/Jul/2019

Dear Dr. Matthew Heath

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

Documents Approved:

Document Name	Document Type	Document Date	Document Version
Email script Clean	Email Script	04/Jul/2018	2
LOI Protocol Clean	Written Consent/Assent	17/Jul/2018	3
par-q	Other Data Collection Instruments	16/Jul/2018	1
Poster Clean	Recruitment Materials	04/Jul/2018	2
Visual Stimulus Data Collection	Other Data Collection Instruments	16/Jul/2018	1

No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB, except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Sincerely,

Nicola Geoghegan-Morphet, Ethics Officer on behalf of Dr. Joseph Gilbert, HSREB Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

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Post-Secondary Education and Degrees: Mercyhurst University
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Heath, M., Petrella, A., Blazevic, J., Lim, D., Pelletier, A., & Belfry, G. R. (2018). A post-exercise facilitation of executive function is independent of aerobically supported metabolic costs. *Neuropsychologia*, 120, 65-74.

Petrella, A., Blazevic, J., Pecora, M., Campbell, J., Heath, M. (2017). A statistical summary presentation in oculomotor control: (Some) evidence from the antisaccade task. (Poster presentation at the Canadian Society for Psychomotor Learning and Sport Psychology-SCAAPS, St John's, Newfoundland and Labrador)

