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Postexercise executive function and cortical hemodynamics during the different phases of the menstrual cycle

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Abstract

Resting cerebral blood flow (CBF) is increased during the luteal (LUT) phase of the menstrual cycle; however, it is unclear whether this change impacts a postexercise executive function (EF) benefit. Female participants (N=16) performed three experimental sessions: a $\dot{V}O_{2peak}$ task and 20-min single bouts of moderate intensity aerobic exercise (i.e., 80% of lactate threshold) during their follicular (FOL) and luteal (LUT) menstrual cycle phases. A separate group of male participants (N=21) additionally completed a $\dot{V}O_{2peak}$ test and a 20-min exercise intervention. Middle cerebral artery velocity (MCAv) was measured during exercise via transcranial Doppler ultrasound to estimate CBF and EF was assessed prior to and immediately after exercise. The MCAv response to exercise and postexercise EF benefit did not vary between FOL and LUT phases or between female and male participants. The present study demonstrates that menstrual cycle status should not limit inclusion of female participants in exercise neuroscience research.

Key Words:

Aerobic

Antisaccades

Cerebral Blood Flow

Estrogen

Follicular

Luteal

Summary for Lay Audience

Biologically female participants have increased resting brain blood flow during the luteal phase of their menstrual cycle. Brain blood flow is increased during a single session of exercise and is thought to be a contributing mechanism to an exercise-based improvement in cognition. The role of increased resting brain blood flow during the luteal phase has not been investigated in the context of exercise-based improvements to cognition. Here, I investigated the brain blood flow response in sixteen female participants by having them complete a twenty-minute cycling session during their follicular and luteal menstrual cycle phases. Twenty-one biologically male participants performed the same exercise session. Results showed no difference in an exercise-based brain blood flow response across menstrual cycle phases or between female and male participants. In addition, menstrual cycle phase and participant-sex did not influence the magnitude of a postexercise improvement in cognition. Accordingly, my dissertation indicates that menstrual cycle status should not serve as a factor limiting the inclusion of female participants in exercise neuroscience research.

Co-Authorship Statements

With the supervision, encouragement and guidance of Dr. Matthew Heath, I completed the present project for this Masters' thesis. With Dr. Matthew Heath, I conceptualized the experiment, designed the research protocol, collected, analyzed and interpreted the data to prepare the manuscript featured in this dissertation. I received support from Dr. Glen Belfry for the conceptualization of the research protocol, analysis and interpretation of data. I obtained support from doctoral student (Dr. Benjamin Tari) for the analysis and interpretation of data. Finally, I received aid from master students (Lauren Guiffre, Lian Buwaidi) and undergraduate student (Grace Chapman) for the collection of data.

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Chapter 1
General Introduction

The goal of my thesis was to evaluate whether two different phases of the menstrual cycle influence cerebral blood flow (CBF) changes to exercise and differentially impact a postexercise executive function (EF) benefit. In developing my thesis document, Chapter 1 provides a general review of: (1) the core components of EF, (2) exercise-mediated benefits to EF following single and chronic bouts of exercise, (3) the neurobiological mechanisms thought to support a postexercise EF benefit, and (4) the neurobiological and presumptive cognitive changes associated with the distinct phases of the menstrual cycle. In turn, Chapter 2 provides the manuscript version of my thesis project.

1.1 Executive Function

EF encompasses the top-down cognitive processes required to make decisions, focus attention, and complete tasks of daily living (Diamond, 2013, Miyake et al., 2000). EF consists of the core components of inhibitory control, working memory, and cognitive flexibility (Diamond, 2013). Inhibitory control is involved in preventing behaviours or distractions that impair goal-directed behaviour; working memory allows for the manipulation of information to complete a specific task; and cognitive flexibility allows for the adjustment of task-directed behaviours (Diamond, 2013). Numerous neuroimaging and lesion studies demonstrate that EF is mediated via the prefrontal cortex (PFC). The prefrontal cortex is responsible for facilitating high-level cognition, planning, problem solving and abstract reasoning essential to EF (Wood & Grafman, 2003). EF is largely localized to three areas of the PFC: (1) dorsolateral prefrontal cortex (DLPFC), (2) orbitofrontal cortex (OFC) and (3) anterior cingulate cortex (ACC) (Fiske & Holmboe, 2019). The DLPFC is involved in top-down modulation, attention, emotional regulation, decision-making and all components of EF (Bagetta & Alexander, 2016). The OFC is largely responsible for regulating emotional and social behaviour (Rolls et al., 2004), whereas the ACC supports adaptive behaviours, error recognition and emotional regulation (Allman et al., 2005). For the purpose of my literature review, I will discuss the DLPFC's role in EF given that the literature has largely examined how differences in estrogen level associated with the menstrual cycle phase influence DLPFC regulated EFs.

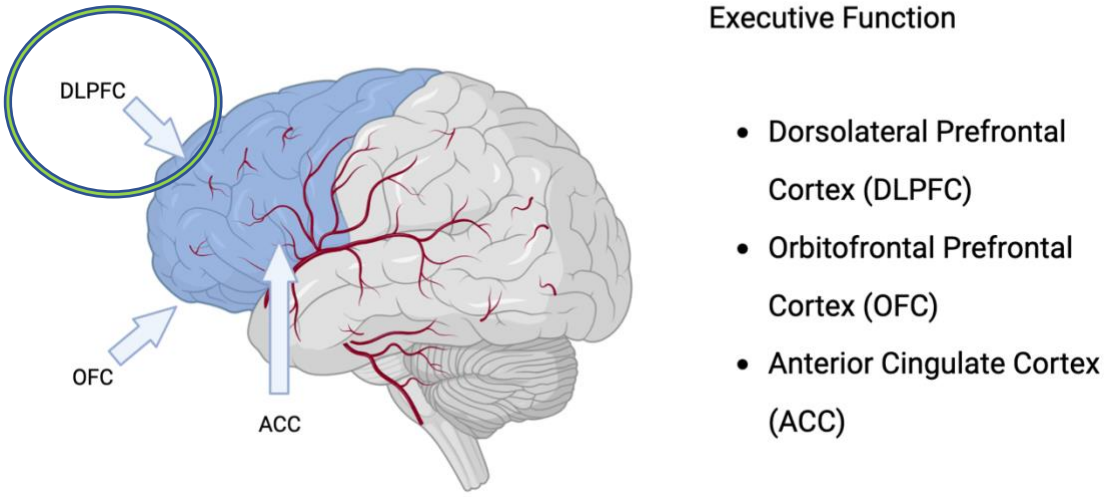

Figure 1. Schematic of the lateral view of the prefrontal lobe.

The inhibitory control component of EF suppresses the interference of stimuli unrelated to a prioritized goal. It includes the subcomponents of: (1) interference control (i.e., focusing on something of interest or priority, and (2) response inhibition (i.e., self-regulation and impulse control). As examples, interference control allows one to focus on reading an article of interest while ignoring distracting stimuli such as a conversation being held in another room. In turn, response inhibition is exercised when withholding an action or response (e.g., eating a cookie) until an appropriate time (e.g., after dinner).

In lab-based settings, the Eriksen flanker (Eriksen and Eriksen, 1974) and Stroop (Stroop, 1935) tasks have been commonly used to assess the inhibitory control component of EF. In the Eriksen flanker task, participants are required to select a response associated with the identity of a central stimulus surrounded by congruent (i.e., "< < < < <") or incongruent (i.e., "< < > < <") flankers. Reaction times (RT) are longer, and errors are more frequent, for incongruent than congruent trials due to the attentional processing required to inhibit the competing response of the flanking arrows (Mullane et al., 2009, Durston et al., 2003, Fan et al., 2002). In turn, the Stroop task entails presenting a word in which the meaning of the word is congruent (i.e., RED) or incongruent (i.e., RED) with the colour of the ink in which the word is presented. As per the Eriksen task, RTs are longer and errors more frequent for incongruent compared to congruent trials – a result attributed to the EF requirement to inhibit a standard response (i.e., word naming) with a non-standard (i.e., colour-naming) one.

Evidence from neuroimaging and clinical neuropsychology has shown that the inhibitory control component of the Eriksen flanker and Stroop tasks is mediated via the DLPFC. For

example, Luks et al., (2010) used voxel-based morphometry (VBM) to determine that persons with atrophy of the left hemisphere DLPFC produced longer RTs and increased errors on incongruent Ericksen trials compared to healthy age-matched controls. Moreover, Blasi et al., (2006) functional magnetic resonance imaging study (fMRI) reported increased bilateral DLPFC activation during performance of "correct" incongruent Ericksen flanker trials. Similarly, Plenger et al., (2016) demonstrated that individuals with traumatic brain injury (TBI) produced longer RTs and increased errors for Stroop incongruent than congruent trials compared to healthy controls. Moreover, Plenger et al. employed functional near-infrared spectroscopy to link this performance decrement to a bilateral decrease in oxygenated hemoglobin in the DLPFC. Stuss and colleagues (2001) found that individuals with DLPFC lobe impairments had significantly longer RTs and increased errors for incongruent Stroop colour naming trials, compared to individuals with posterior lesions and healthy controls. Therefore, there is sufficient neuroimaging and clinical evidence to assert that the DLPFC supports the inhibitory control component of EF.

The working memory component of EF allows for the manipulation of information/stimuli to complete a specific task (Diamond, 2013). Two tasks commonly used to assess working memory are the n-back (Kirchner, 1958) and Tower of London (TOL) (Shallice, 1982) tasks. In the n-back task, participants report whether a currently presented stimuli matches a serially presented stimuli 'n' items back (i.e., does a current stimulus match a stimulus presented one, two or three items "back" in a serial list?). The value for 'n' (i.e., 1-back, 2-back, 3-back) is increased to increase working memory processing demands. For the Tower of London task, participants manipulate the configuration of a series of test items until they match an exemplar image and efficiency on this task is determined via the number of moves required to match the exemplar image. The Tower of London task is thought to gauge working memory because the sequence of moves necessary to complete the task must be remembered and executed accordingly (D'Antuono et al., 2017).

Evidence from neuroimaging and behavioural studies demonstrate that the working memory component of the n-back and Tower of London task is mediated via the DLPFC. For example, Jonides et al., (1997) employed positron emission tomography to demonstrate that healthy controls show increased DLPFC activity as a function of n-back complexity (i.e., 1-back vs. 3-back). Similarly, Huang et al.'s (2019) magnetoencephalography (MEG) work showed that

individuals with symptomatic traumatic brain injury demonstrated decreased source-localized DLPFC activity during n-back performance compared to healthy controls. Neuroimaging and clinical neuropsychology work has linked Tower of London performance efficiency to DLPFC activity. Baker et al., (1996) demonstrated that in healthy young to middle aged adults, there was increased regional CBF in the DLPFC during performance of the difficult conditions of the TOL, as well as increased RT and errors. Further, Owen et al.,'s (1990) lesion study demonstrated that individuals with unilateral or bilateral frontal lobe excisions produced significantly lower Tower of London performance compared to healthy controls. Individuals in the lesion group completed the given problems with more moves than healthy controls and took more time for problem completion. Hence, evidence demonstrates that the DLPFC mediates working memory.

Cognitive flexibility reflects adaptable thinking to support set-shifting and the ability to alternate between different tasks. Cognitive flexibility is commonly assessed via a task-switching paradigm involving the performance of standard and non-standard tasks arranged in an AABB paradigm (Rogers & Monsell, 1995). For example, congruent (i.e., standard task) and incongruent (non-standard) Stroop trials arranged in an AABB paradigm result in an increase in RT for a standard task preceded by a non-standard task, whereas as similar "switch-cost" is not observed when a standard task precedes a non-standard task. The switch-cost has been attributed to an EF task-set required to implement a non-standard response that persists inertially and delays the planning of a subsequent standard task (Alport et al., 1994). In turn, a cost is not associated with switching from a standard to a non-standard task because the latter is implemented independent of an executive-mediated task-set. Indeed, event-related brain potential work by Weiler et al., (2015) showed that the amplitude of the P300 waveform (i.e., a component reflecting EF) associated with a standard trial was increased when preceded by a non-standard trial. This result was taken to evince the persistent activation of a non-standard task-set. As well, DLPFC lesions have been shown to increase task-switching errors and increase RTs for standard task-switch trials. Hence, and in line with inhibitory control and working memory there is evidence to assert that the core components of EF are – in part – mediated via activity of the DLPFC.

1.2 The Antisaccade Task

Prosaccades require a goal-directed eye movement (i.e., saccade) to a presented target and are mediated largely independent of top-down EF (Pierrot-Deseilligny et al., 1995). In turn,

antisaccades are an EF task requiring that an individual saccade mirror-symmetrical to a target (Hallet, 1978, Fischer and Weber, 1992). Antisasccades produce longer RTs, (Hallet, 1978), increased directional errors (i.e., a prosaccade instead of an instructed antisaccade) and increased endpoint errors (Gillen and Heath, 2014) compared to prosaccades. The antisaccade behavioural costs have been attributed to the top-down EF of suppressing a pre-potent prosaccade (i.e., inhibitory control) and the 180° spatial transposition of a target's coordinates (Munoz and Everling, 2004). Moreover, extensive neuroimaging in humans, as well as single-cell and transient cooling studies in non-human primates, has shown that the evocation of a directionally correct antisaccade is mediated via the DLPFC (for review see Everling and Johnston, 2013).

1.3 Exercise and Executive Function

Chronic aerobic and/or resistance training improves EF (see Chen et al., 2020, Engeroff et al., 2018, Colcombe & Kramer, 2003). For example, cognitively healthy older adults of high fitness, or those that participated in a six-month aerobic training intervention, showed increased DLPFC activation (as indicated via fMRI) and improved Flanker task incongruent trial RTs (and accuracy) compared to low-fit individuals and those that did not participate in an exercise intervention (Colcombe et al., 2004). In addition to chronic exercise, there is strong support for the role of a single bout of aerobic exercise in improving each core component of EF. Chen et al.'s (2020) meta-analysis reported that cognitively healthy older adults performing a single bout of moderate-intensity aerobic exercise, (defined as 55-70% maximum predicted heart rate: HR_{max}) showed an improvement to each core component of EF. Moreover, the seminal meta-analysis by Chang et al., (2012) reported that a 20-min single bout of *moderate*-intensity aerobic exercise optimizes the postexercise EF benefit and that high-fit individuals accrue a larger benefit than their low-fit counterparts.

The inhibitory control component of EF has been shown to be positively influenced after a single bout of moderate-intensity aerobic exercise. For example, Tempest et al., (2017) reported that RT for incongruent trials of the Flanker task were shorter following a single bout of aerobic exercise at 10% above the ventilatory threshold (e.g., 165 ± 44 W) compared to very-low intensity exercise (<30 W). Further, Tempest et al., employed near-infrared spectroscopy (NIRS) to show that this improvement was linked to increased oxygenation in prefrontal cortical regions. In turn, Alves et al., (2012) found that RT for the non-standard colour-naming condition of the Stroop task was reduced after healthy older women (i.e., postmenopausal) performed 30

min of walking at 50-60% heart rate reserve (HRR= max HR - resting HR) compared to those in a non-exercise control condition. As well, Lucas et al.'s (2012) Stroop task findings indicated that young and older healthy adults produced shorter RTs following a 16-min session of exercise (i.e., 70% heart rate range: $HR_{max} - HR_{min}$) compared to 30% of heart rate range (16 minutes in total). Finally, improvements to inhibitory control following a single session of 65% HR_{max} stationary cycling were documented wherein RT for incongruent trials of the Stroop task were decreased postexercise compared to a non-exercise control (Zimmer et al., 2016). Thus, inhibitory control is improved following a single bout of moderate-intensity aerobic exercise.

The significance of a single bout of moderate-intensity aerobic exercise on the working memory component of EF has also been frequently documented in the literature. Cognitively healthy older adults showed improved accuracy and RT for the 2-back task following a 20-min bout of stationary cycling at 65% HR_{max} compared to passive cycling (mechanically driven cycle ergometer flywheel) (Voss et al., 2020, Tari et al., 2023). Working memory improvements were also demonstrated in Park and Etnier's (2019) work involving a 20-min bout of exercise (cycling at 64-76% age-predicted maximal HR) wherein healthy adolescents demonstrated improved postexercise performance on the Tower of London task.

A single bout exercise has also been shown to positively benefit the cognitive flexibility component of EF. For example, Bae and Masaki (2019) reported that healthy young adults that completed 30 minutes of treadmill running at 70% HR_{max} demonstrated shorter RTs on task-switch trials compared to baseline and showed reduced P300 latencies indicative of improved EF. A single bout of moderate-intensity aerobic exercise has also been shown to improve cognitive flexibility in children with attention deficit hyperactivity disorder (ADHD). Hung et al., (2016) demonstrated that children with ADHD had increased P300 amplitudes when performing task-switch trials after 30 minutes of treadmill running at 50%-70% HRR. Hence, a single bout of moderate-intensity aerobic exercise supports the cognitive flexibility component of EF.

A wealth of studies conducted by my lab group demonstrate postexercise EF benefits following a single bout of aerobic exercise via the pro- and antisaccade task (e.g., Heath et al., 2018, Petrella et al., 2019, Shukla et al., 2022). For example, Heath et al. found that healthy young adults show a selective postexercise reduction in antisaccade RT across a continuum of exercise intensities and is a result Petrella et al. extended to cognitively healthy older adults. As

well, Shukla and Heath (2022) demonstrated that switch-costs for pro- and antisaccade tasks arranged in an AABB paradigm are reduced postexercise. Thus, the antisaccade task provides the resolution for detecting subtle and exercise-specific EF benefits in inhibitory control and cognitive flexibility.

1.4 Mechanisms associated with an exercise-mediated EF benefit

1.4.1 Increase in brain-derived neurotrophic factor (BDNF) during exercise and EF

Participation in chronic moderate intensity aerobic exercise is thought to be associated with a number of neurophysiological changes that promote long-term improvements in EF (de Azevedo et al., 2019, de Assis & de Almondes, 2017). One such mechanism is increased brain-derived neurotrophic factor (BDNF) released during exercise that is thought to support neural growth/survival and energy regulation (Walsh & Tschakovsky, 2018). For example, Griffin et al., (2011) showed that five weeks of aerobic exercise increased serum BDNF and was associated with improved incongruent trial Stroop task performance. As well, Erickson et al., (2011) reported a significant relationship between enhanced hippocampal volume and increased serum BDNF in healthy older adults who performed a chronic walking program. There is also some support in the literature for the utility of a single bout of moderate-intensity aerobic exercise increasing serum BDNF and improving EF. Hwang et al., (2016) demonstrated an increase in serum BDNF during a single 20-minute bout of treadmill running at 85-90% $\dot{V}O_{2max}$ was related to improved EF performance as assessed via the Stroop task. Notably, however, Tsai et al., (2016) showed that a postexercise improvement in a task-switching paradigm following a 30-minute bout of treadmill running at 60% individual $\dot{V}O_{2max}$ was unrelated to an increase in serum-BDNF. Hence, it remains unclear as to whether serum-BDNF is a primary moderator associated with a single bout postexercise EF benefit.

1.4.2 Increase in catecholamines during exercise and EF

Participation in a single bout of moderate intensity aerobic exercise elicits an exercise-mediated increase in catecholamines such as norepinephrine (NA) and dopamine (DA) (Arnsten and Li, 2005, Arnsten, 2011). In particular, an exercise-triggered increase in the concentration of catecholamines by the hypothalamus is thought to enhance EF via “upregulation” of NA and DA receptors in the PFC (Clark & Noudoost, 2014). Further, NA and DA are thought to reduce background neural noise in the prefrontal lobe and improve EF facilitation (Mesulam, 1990).

Dopamine reward signaling is also mediated by PFC circuitry and thus may be facilitated via an exercise-mediated increase in catecholamines. Davranche et al., (2009) reported that a 20-minute bout of stationary cycling at 50-80% of maximum aerobic power improved Ericksen flanker task performance and was related to the increased concentration of norepinephrine and dopamine. These findings suggest that increases in catecholamine concentration during aerobic exercise mediate the improvement in EF. In contrast, it has been shown that if aerobic exercise is performed at too high of an intensity, then arousal effects associated with catecholamine concentrations may transition into "stress effects" and impair PFC activity and associated EF processes (Arnsten et al., 1997, Dietrich and Audiffren, 2011).

1.4.3 Increase in resting state functional connectivity and EF

A third mechanism linked to a postexercise EF benefit is improved resting state functional connectivity (RSFC), or the fluctuation of blood flow and oxygenation between functionally related cortical regions (Biswal et al., 1995). For example, Prehn et al., (2019) reported that RSFC in the DLPFC was increased in older overweight women after a 6-month moderate intensity aerobic exercise program compared to those in a non-aerobic stretching/toning program. As well, an 8-week skipping-rope aerobic intervention in children with and without ADHD was observed to be related to increased regional homogeneity (i.e., an indicator of RSFC) and was associated with improved Flanker task performance (Jiang et al., 2022). In contrast, Rajab et al.,'s (2014) fMRI study showed healthy young adults that completed a single bout of aerobic exercise (70% HR_{max}) did not demonstrate pre- to postexercise changes in RSFC. Hence, evidence favouring an improvement in RSFC to a postexercise EF benefit is equivocal.

1.4.4 Aerobic exercise increases CBF which improves EF

A fourth mechanism attributed to the postexercise EF benefit is an exercise-mediated increase in cerebral blood flow (CBF). It is well established in the literature that neural efficiency is improved through mechanical and temperature-based changes within the neural circuitry due to increased CBF (Moore & Cao, 2008). Indeed, exercise results in a systemic increase in CBF due to the regulatory actions of complex mechanisms including the alteration of vascular tone and perfusion pressure, wherein sufficient blood flow to the cerebral vasculature must be maintained (Ogoh et al., 2009). This exercise-mediated increase in CBF was found to be reliably related to the magnitude of a postexercise EF benefit (Tari et al., 2020). Similarly, Shirzad et al, (2022) reported than an increase in CBF associated with passive cycling (using mechanically driven

cycle ergometer flywheel) resulted in an EF benefit. This finding is noteworthy as it shows that in passive exercise, CBF is increased independent of the metabolic demands required of aerobic (i.e., active) exercise. Hence, an increase in CBF has been observed independent of the metabolic demands of volitional muscle activation.

1.5 The Menstrual Cycle

A woman's menstrual cycle begins around the ages of 8.5 to 13 years (Mihm et al., 2011) and supports the development and maintenance of female sexual and reproductive characteristics. The menstrual cycle repeats every 21-35 days for the preparation of the pre-menopausal woman's uterus for conception if fertilization occurs or shedding of the uterine lining if fertilization does not occur. The menstrual cycle is regulated by the same hormones that are crucial for the development and maintenance of female reproductive characteristics, including estrogen, progesterone, follicle stimulating hormone (FSH) and luteinizing stimulating hormone (LH) (Mayo, 1997). In the context of the menstrual cycle, estrogen and progesterone thicken the endometrium, FSH stimulates the development of the follicle and LH surges to trigger ovulation (Mayo, 1997). The average menstrual cycle is about 28 days in length (range of 21 - 35 days) (Mihm et al., 2011). The menstrual cycle begins with menses or menstruation during the follicular (FOL) phase and usually lasts for five days. During the FOL phase, follicular-stimulating hormone (FSH) stimulates the production of follicles on the surface of the ovary that will mature into an egg (days 1 - 14) (Schipper et al., 1998). During the FOL phase, the concentration of estrogen and progesterone are low, but rise to peak concentration at the end of the phase (Farage et al., 2009). As estrogen and progesterone increase, the uterine lining thickens during the FOL phase in case of successful fertilization. Peak estrogen concentration triggers the brain to release a large amount of LH (i.e., the "LH surge") and FSH to trigger ovulation. Ovulation follows, wherein a mature egg is released from a follicle in the ovary and then migrates to the uterus where it may be fertilized and result in pregnancy (days 12 - 16) (Schipper et al., 1998). Following ovulation, the ruptured follicle is reorganized into the corpus luteum which is a crucial hormone of the luteal (LUT) phase (days 15 - 28) and results in the release of progesterone and estrogen (Silberstein & Merriam, 2000). The corpus luteum produces more progesterone for thickening of the uterine lining if a fertilized egg implants in the uterine lining (Mihm et al., 2011). If no implantation occurs, the corpus luteum is broken down,

progesterone and estrogen concentration significantly decrease back to baseline and the uterine lining sheds again (Mihm et al., 2011, Farage et al., 2009) (see Figure 2).

High concentration of estrogen has been shown to increase basal CBF via cerebral vasodilation, wherein estrogen increases the production or sensitivity of endothelium derived vasoactive factors such as nitric oxide (NO) (Robison et al., 2019). This supports the well documented finding of increased resting CBF during the LUT phase (Brackley et al., 1999, Peltonen et al., 2016). For example, Brackley et al., (1999) measured middle cerebral artery velocity (MCAv) via transcranial Doppler ultrasound (TCD) to estimate CBF and reported increased MCAv during the LUT phase compared to the FOL phase – a result attributed to an estrogen-based reduction in cerebrovascular impedance. Additionally, Peltonen et al., (2016) demonstrated that cyclooxygenase (COX) (estrogen producing enzyme) inhibitor decreased the difference in basal cerebrovascular conductance (CVCi) and again demonstrated estrogen's role in regulating CBF.

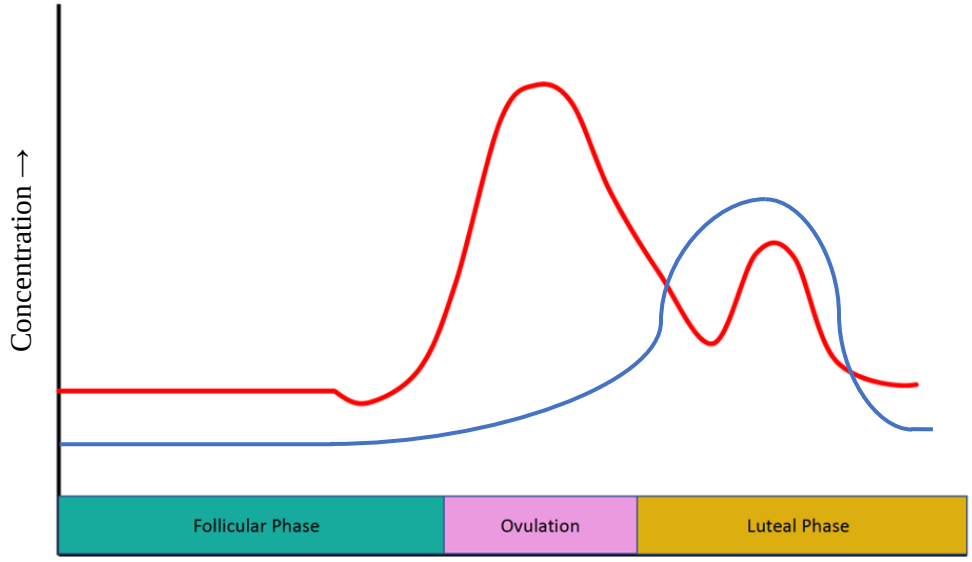

Figure 2. Schematic of estrogen and progesterone concentration in the follicular, ovulatory and luteal phases of the menstrual cycle.

1.6 Role of Menstrual Cycle in Cognitive Abilities

The literature reports mixed results regarding whether the menstrual cycle impacts EF and other components of cognition (Sundström Poromaa and Gingnell, 2014, Fernández et al., 2003). An initial hypothesis that predominated the cognitive sciences was that biologically male

participants perform better on tasks of visuospatial ability (i.e., the mental rotation task), whereas biologically female participants show better performance on tasks of verbal memory and verbal fluency when estrogen concentration is greatest (i.e., LUT phase) (Fernández et al., 2003, Linn & Petersen., 1985). The mental rotation task (MRT) assesses visuospatial EF and requires that an individual identify whether a target stimulus matches an exemplar (Shepard and Metzler, 1971). Hausmann et al., (2000) and Schöning et al., (2007) demonstrated that healthy young female participants demonstrated improved performance on the mental rotation task during the FOL compared to LUT phase and observed that estrogen level was negatively correlated to task performance. Similarly, Schöning et al., (2007) demonstrated that male participants scored more problems correctly in a mental rotation task than female participants in the LUT phase. Regarding verbal memory, Postma et al., (1999) found that females adopted more of a verbal processing strategy for completion of a computerized mental rotation task in the LUT phase compared to the FOL phase. As well, Solís-Ortiz et al., (2008) demonstrated that healthy women with normal menstrual cycles had improved attention during the LUT phase compared to the FOL phase. Notably, however, Sundström Poromma and Gingnell's (2014) excellent review reported there is not sufficient evidence that menstrual cycle status differentially influences cognitive performance and the authors further concluded that differences in sexually dimorphic tasks – including those probing frontal lobe EF – are small and challenging to replicate. Moreover, Sundström Poromma and Gingnell asserted that those studies reporting menstrual cycle- and sex-specific differences in cognitive abilities are generally of low-quality and do not offer sound methodological control. This view is echoed in Le et al.'s (2020) more recent review concluding there is not compelling evidence to assert cognition and EF variations across the menstrual cycle.

1.7 Effect of Phase of the Menstrual Cycle on the Postexercise Executive Function Benefit

My thesis project seeks to examine whether the menstrual cycle impacts postexercise benefits to EF and whether menstrual cycle changes impact an exercise-mediated increase in CBF. My thesis study was inspired by findings from Dirk et al., (2020) showing that FOL and LUT phases of the menstrual cycle provide an equivalent magnitude postexercise EF benefit. In particular, Dirk et al., (2020) had healthy young female participants (18-26 years) perform a 20-min single bout of cycle ergometer exercise during the FOL (on days 2 or 3) and LUT phases (~day 21) of

their menstrual cycles. Prior to and immediately following each exercise session, participants completed a series of pro- and antisaccade trials. Antisaccades were selected to assess EF because they provide the resolution to detect subtle exercise-based changes in EF (see details above). Dirk et al., (2020) showed that antisaccade – but not prosaccade – RTs were shorter postexercise and thus provide evidence that exercise provides an EF-specific performance benefit. More notably, both null hypothesis and equivalence tests indicate that the magnitude of the EF benefit did not vary across FOL and LUT phases. Accordingly, Dirk et al., (2020) concluded that female participants should not be excluded from exercise neuroscience research given that menstrual cycle status does not impact postexercise EF benefits.

One important issue not addressed by Dirk et al., (2020) was a measure of CBF to evaluate whether the CBF response to exercise – and associated postexercise EF benefits – vary with FOL and LUT menstrual cycle phases. This is a salient question because decreased basal vascular impedance and an associated exercise benefit in the LUT phase may be associated with a larger postexercise EF benefit (for review of CBF response to exercise, see Ogoh and Ainslie, 2009). To my knowledge, however, no research has directly evaluated CBF response to exercise as a function of menstrual cycle phase. A second area not addressed by Dirk et al., is whether postexercise EF benefits vary between female and male participants and whether menstrual cycle phase impacts any between-group difference(s) (i.e., Dirk et al.'s sample included only female participants). Accordingly, the present investigation had female (FOL and LUT phase) and male participants complete a single bout of moderate intensity (80% of participant-specific estimated lactate threshold) aerobic exercise (via cycle ergometer) and measured real-time MCAv via TCD to provide an estimate of baseline and steady state exercise changes in CBF. Pre- and postexercise EF was measured via the pro- and antisaccade task. In terms of research predictions, if menstrual cycle phases differentially influence an exercise-based change in CBF, then a postexercise reduction in antisaccade RTs may vary in *magnitude* between FOL and LUT phases, and menstrual cycle phase may elicit differences in postexercise EF benefits between male and female participants. In turn, if menstrual cycle phases do not influence exercise-based changes in CBF and/or EF then the magnitude of a postexercise EF benefit should not vary between FOL and LUT phases or between female and male participants. Evidence favouring the latter prediction would serve to support increased inclusion of female participants in research examining exercise-based benefits to EF and cognition.

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Chapter 2
Exercise-mediated changes in cerebral blood flow and postexercise executive function benefits do not vary across follicular and luteal menstrual cycle phases

2.1 Introduction

Executive function (EF) refers to the top-down cognitive processes involved in the effortful actions and behaviours associated with tasks of daily living (Diamond, 2013). EF includes the core components of inhibitory control, working memory and cognitive flexibility (Diamond, 2013) and neuroimaging and lesion studies have shown that EF is supported by an extensive frontoparietal network (for review see Nowrangi et al., 2014). Notably, a single bout of aerobic or resistance exercise benefits EF (see meta-analyses Chang et al., 2012, Lambourne and Tomporowski, 2010, Ludyga et al., 2018). For example, Byun et al., (2014) reported that healthy individuals had reduced errors and reaction time (RT) on incongruent trials of an inhibitory control, i.e., Stroop task after a 10-min single bout of light intensity cycling ergometry (30% $\dot{V}O_{2peak}$) and was associated with increased task-based activity in the dorsolateral prefrontal cortex (DLPFC). A strong candidate mechanism for the improvement in EF is outlined in Moore and Cao's (2008) hemo-neural hypothesis wherein an increase in CBF elicits mechanical- and temperature-based changes to the brain's neural and glia networks that improve EF network processing efficiency. Indeed, Tari et al., (2020) demonstrated that CBF was increased during 10-minutes of aerobic exercise and was reliably correlated to a postexercise EF benefit. Tari et al. also showed that an increase in CBF independent of the metabolic demands of exercise, (i.e., via a hypercapnic environment (5% CO_2)) improves EF.

A limitation of the current exercise neuroscience/psychology literature is that biologically female participants are underrepresented. To illustrate this, Chang et al.'s (2012) seminal meta-analysis reported that of the 1034 effect sizes associated with single bout exercise and cognitive benefits only 6% included female participants, while 47% of studies included male participants and 40% of studies included both male and female participants. An oft-reported rationale for excluding female participants is that ovarian hormonal variations associated with female participants' menstrual cycle elicits differential effects on performance and psychological variables (Linn & Petersen., 1985). Indeed, ovarian hormone (e.g., estrogen, progesterone) concentrations vary across the menstrual cycle and are lowest in the follicular (FOL; i.e., days 1-13 of menstrual cycle) than luteal (LUT; i.e., days 21-28 of menstrual cycle) phase of a typical 28-day menstrual cycle. Given these differences, some research has reported that the menstrual cycle elicits sexually dimorphic cognitive skills such that visuospatial and EF abilities are increased in the FOL phase. For example, Hausmann et al., (2000) had female participants

(N=8) complete a mental rotation task (i.e., a visuospatial EF task) and reported improved performance in the FOL as compared to the LUT phase and concluded that EF "[…] is sensitive to hormonal fluctuations over the menstrual cycle" (p. 1249) (see also Broverman et al., 1981; Hampson, 1990; Phillips and Silverman, 1997). As well, some evidence has reported that verbal memory (e.g., Phillips and Sherwin, 1992; Postma et al., 1999, Rosenberg and Park, 2002, but see Mordecai, Rubin and Maki, 2008) and sustained attention/vigilance are improved during the LUT compared to FOL menstrual cycle phase (Pletzer, Harris and Ortner, 2017; Solís-Ortiz and Corsi-Cabrera, 2008). Notably, however, Sundström Poromma and Gingnell's (2014) excellent review reported there is not sufficient evidence that menstrual cycle status differentially influences cognitive performance. The authors further concluded that differences in sexually dimorphic tasks – including those probing frontal lobe EF – are small and challenging to replicate (Sundström Poromma and Gingnell., 2014). This view is echoed in Le et al.'s (2020) more recent review concluding there is not compelling evidence to assert cognition and EF variations across the menstrual cycle.

Only a single study examined whether menstrual cycle phases differentially influence an EF response to exercise (Dirk et al., 2020). In that work, biologically female participants (N=16) performed separate 20-min single bouts of moderate intensity exercise (via cycle ergometer) during the early-FOL and mid-LUT phases of their menstrual cycle and pre- and postexercise EF was assessed via the antisaccade task (see details below). Dirk et al., was predicated on *some* evidence from the cognitive sciences (see above) reporting that the menstrual cycle impacts EF and evidence reporting that the vasoactive effects (e.g., decreased cerebrovascular impedance) of increased ovarian hormones during the LUT phase increase basal CBF (Brackley, Ramsay, Pipkin, Rubin, 1999; Krejza, Mariak, Huba, Wolczynski, Lweko, 2001; Peltonen, Harrell, Aleckson, Laplante et al., 2016; but see Korad, Munddel, Fan and Perry, 2022). Dirk et al. reported a 7% pre- to postexercise improvement in EF with null hypothesis and equivalence tests demonstrating the *magnitude* of the benefit did not vary across FOL and LUT phases. Accordingly, Dirk et al. concluded that menstrual cycle status (or knowledge thereof) should not serve as a factor limiting inclusion of female participants in research examining postexercise EF benefits.

One notable limitation of Dirk et al., (2020) is that the authors did not measure CBF during exercise. As a result, it is unclear whether baseline to steady state changes in CBF relate

to the magnitude of postexercise EF benefits across FOL and LUT menstrual cycle phases. This is a salient consideration given that the LUT phase is associated with increased resting CBF and decreased cerebrovascular resistance. A second limitation of Dirk et al. is that it did not include a separate corpus of male participants. As a result, it is unclear whether CBF changes to exercise and associated postexercise EF benefits vary between female and male participants. In the present study, biologically female and male participants completed an initial $\dot{V}O_{2peak}$ test to determine participant-specific measures of a "moderate" exercise intensity (i.e., 80% of lactate threshold). In subsequent sessions, female participants completed 20-min single bouts of cycle ergometry at 80% of lactate threshold during the FOL and LUT phases of their menstrual cycle. In turn, male participants completed a single session of matched intensity cycle ergometry. Middle cerebral artery velocity (MCAv) was measured via transcranial Doppler ultrasound (TCD) to provide an estimate of baseline to steady state changes in CBF and pre- and postexercise EF was examined via the pro- and antisaccade task. Prosaccades require a goal-directed eye movement (i.e., saccade) to the location of an exogenously presented target, whereas antisaccades require a response mirror-symmetrical to the target. Antisaccades produce longer reaction times (RT) (Hallett, 1978) and less accurate and more variable endpoints (Gillen and Heath, 2014) than their prosaccade counterparts. Extensive neuroimaging studies in humans, and single-cell recording and transient cooling studies in non-human primates, have shown that antisaccade behavioural 'costs' reflect the time-consuming demands of top-down EF (for reviews see Munoz and Everling 2004; Everling and Johnston 2013). In turn, prosaccades are mediated largely independent of EF via direct retinotopic projections to the superior colliculus (Pierrot-Deseilligny et al., 1995, Wurtz & Albano, 1980). Several studies have shown that a single bout of aerobic exercise across a continuum of intensities results in a pre- to postexercise reduction in antisaccade – but not prosaccade – reaction times (Dirk et al., 2020 Petrella et al., 2019; Heath et al., 2019; Samani and Heath 2018; Tari et al., 2022; Shirzad et al., 2022; Shukla et al., 2022); that is, results evince a selective postexercise EF benefit.

In terms of research predictions, if menstrual cycle phases differentially influence an exercise-based change in CBF, then a postexercise reduction in antisaccade RTs may vary in *magnitude* between FOL and LUT phases, and menstrual cycle phase may elicit differences in postexercise EF benefits between male and female participants. In turn, if menstrual cycle phases do not influence exercise-based changes in CBF and/or EF then the magnitude of a

postexercise EF benefit should not vary between FOL and LUT phases or between female and male participants. Evidence favouring the latter prediction would serve to support increased inclusion of female participants in research examining exercise-based benefits to EF and cognition.

2.2 Methods

2.2.1 Participants

Sixteen self-identified biologically female (18–28 years of age, average=22.4, SD=2.8) and 21 male (18–28 years of age, average=23.3, SD=2.3) undergraduate and graduate students were recruited from the School of Kinesiology, University of Western Ontario. Sample size was determined *a priori* based on Dirk et al.'s (2020) reported effect size (d_z=0.92, N=15) for pre- to postexercise changes in antisaccade RT. Inclusion criteria included: self-report of normal frequency menstrual status and not pregnant (female participants only); normal or corrected-to-normal vision; able to read and write in English; non-smoker; no history of neurological impairment (including concussion) or neuropsychiatric disorder; not taking medication that might alter cardiorespiratory or metabolic responses to exercise; and not suffering from a current illness that could affect daily activities (e.g., flu-like symptoms). Exclusion criteria for female participants included: irregular menstrual cycles (<21 or > 35 days); individuals who appeared to be anovulatory according to self-report, or LUT phase deficient and/or ovulation could not be verified using urinary hormone testing; individuals who reported any use of hormonal contraceptive within 6 months of participation in the study (intrauterine device (IUD) or hormonal birth control). Participants were instructed to refrain from alcohol and rigorous exercise for 12 h prior to each exercise session, were asked to get 8 h of sleep the night before an exercise session and consume 555 ml of water one hour prior to an experimental session. Participants were also asked to consume their typical breakfast before each session but avoid having a heavy meal immediately before participating. Participants self-reported adhering to these instructions.

All participants obtained a full score on the 2019 Physical Activity Readiness Questionnaire (PAR-Q+) (Warburton et al., 2011) and completed the Godin Leisure-Time Exercise Questionnaire (GLTEQ) (Godin, 2011). The average score on the GLETQ was (57, SD = 21: range: 25 to 120) and therefore indicated that all participants were recreationally active. Prior to any study-related event, participants read a letter of information and provided informed

written consent for a protocol approved by the Health Sciences Research Ethics Board, University of Western Ontario (ID: 112758). This study conformed to the ethical standards set by the most recent iteration of the Declaration of Helsinki with the exception that participants were not registered in a database.

2.2.2. Experimental Overview

Female and male participants both completed a $\dot{V}O_{2peak}$ test. Female participants completed two additional experimental sessions while male participants completed one experimental session. All participants completed an initial incremental ramp test – via cycle ergometer – to volitional exhaustion to determine participant-specific estimated lactate threshold (LT) and peak oxygen consumption ($\dot{V}O_{2peak}$). A confirmation ride was not included (i.e., $\dot{V}O_{2max}$) since participants were from the School of Kinesiology and familiar with performing volitional tests to exhaustion (Chidnok, 2013; Tari et al., 2020). Subsequently, on separate days female participants completed 20-min single bout sessions of cycle ergometry at 80% of LT during the FOL and LUT phases of their menstrual cycle. In turn, male participants completed a single 20-min session of cycle ergometry at 80% of LT. For each exercise session, MCAv was measured via TCD to provide an estimate of baseline to steady state changes in CBF. Prior to and immediately after each 20-min exercise session, participants completed an oculomotor assessment involving pro- and antisaccades to examine putative exercise-mediated changes in EF. Exercise duration (20-min) and intensity (80% of LT) was selected based on work showing that such an intervention provides a reliable postexercise EF benefit (Dirk et al., 2020, Heath et al., 2018; Samani and Heath 2018; Petrella et al., 2019; Shukla and Heath, 2020; Tari et al., 2020).

2.2.3. Menstrual cycle verification

Female participants self-reported to one of the researchers (PP) information about the final day of their last completed period and their average period length. For this study, the beginning of the FOL phase (i.e., day 1) was established by the onset of menstrual flow (menstruation), whereas onset of the LUT phase was verified using experimenter-provided urinary ovulation sticks (AccuMed 100-Count Ovulation (LH) Test Strips, Houston, TX) that detect a surge in luteinizing hormone (LH) and precedes ovulation by 24–36 h. Female participants were instructed to begin using the testing sticks on day seven of their menstrual cycle and to continue using them until a positive test for LH was detected (i.e., as indicated by the manufacturer's instructions). Positive tests were verified by the researcher (PP) through photographic evidence.

Exercise testing (see details below) in the FOL phase occurred on day 2 or 3 of the menstrual cycle (i.e., early FOL phase), whereas testing in the LUT phase began 4 d after a positive test was confirmed via the ovulation test strips (i.e., LUT: ~day 17 for a 28-d cycle). The time points for the FOL and LUT phases were selected because they represent when ovarian hormone concentration (e.g., estrogen and progesterone) are at their lowest and highest concentrations, respectively (Nevo et al., 2007).

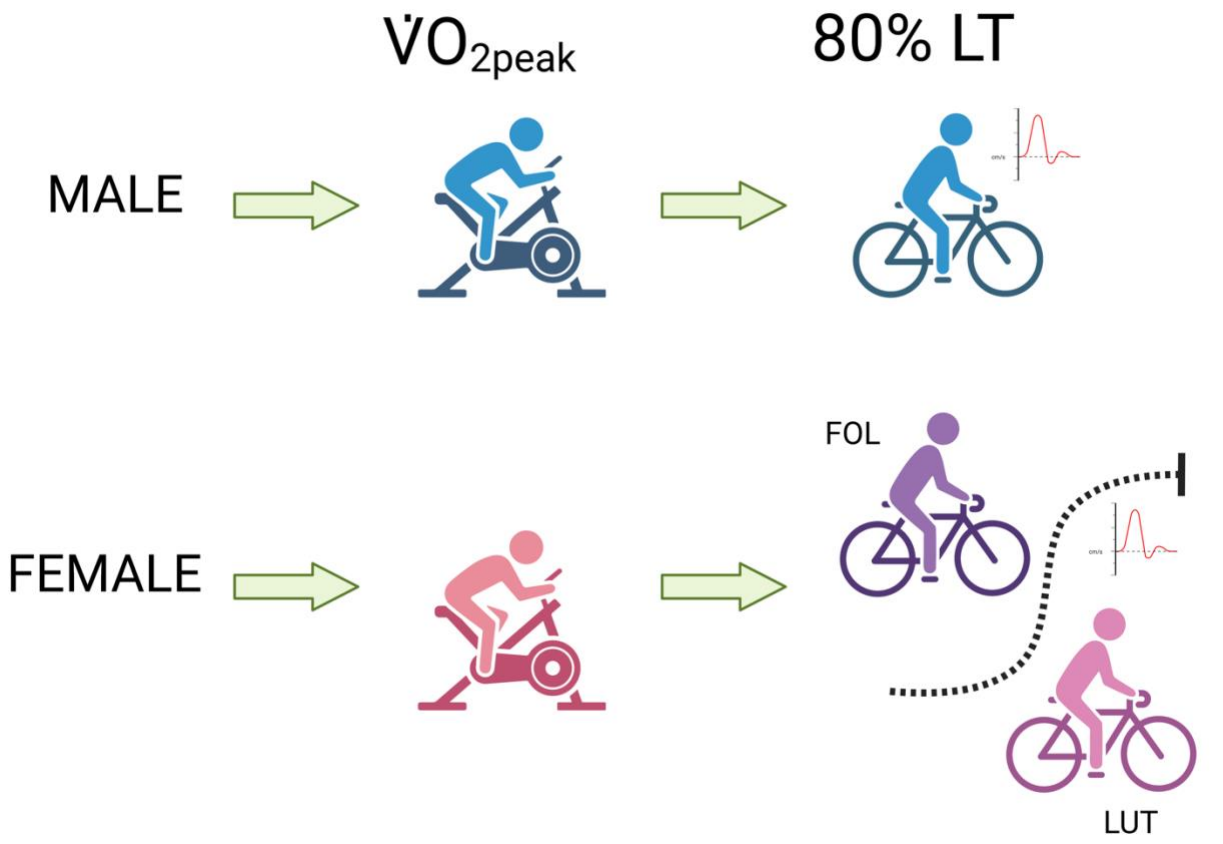
2.2.4. Apparatus and Procedures

$\dot{V}O_{2peak}$ assessment and estimate of LT. Female and male participants completed two and one intervention-based exercise session(s) via a cycle ergometer (Velotron; RaceMater, Seattle, WA), respectively. To determine a participant-specific work rate for each exercise session, participants first completed an incremental ramp test to volitional exhaustion to determine estimated LT and $\dot{V}O_{2peak}$. For this assessment, participants pedaled on the cycle ergometer and completed a 2-min baseline ride at 20 W, which was followed by an incremental ramp test to volitional exhaustion with a work rate increment of 20 $W \cdot min^{-1}$ and pedal cadence set at 70 rpm. A work rate increment of 15 $W \cdot min^{-1}$ was used for individuals who indicated a difficulty with the work rate increment of 20 $W \cdot min^{-1}$. Strong verbal encouragement was provided to participants to facilitate peak effort. The $\dot{V}O_{2peak}$ assessment was performed irrespective of menstrual cycle phase given work demonstrating that menstrual cycle phase does not impact $\dot{V}O_{2peak}$ or power output (Dean et al., 2003). During the $\dot{V}O_{2peak}$ assessment, participants wore a nose clip (i.e., to prevent breathing from the nose) and a rubber mouthpiece. Gas collection flow rates were measured via a bidirectional turbine of 100-mL dead space (VMM 100; Alpha Technologies, Laguna Hills, CA) and pneumotach (Model 4813; Hans Rudolph, Shawnee, KS). Inspired and expired gases were analyzed at the mouth for concentrations of O_2, CO_2, and N_2 by mass spectrometry (Quark RMR, COSMED USA Inc., Concord, CA) following calibration with a precision analyzed gas mixture. Changes in gas concentrations were aligned with gas volumes by measuring the time delay for a square wave bolus of gas passing the turbine to the resulting changes in fractional gas concentrations as measured by the mass spectrometer. Data were collected at 20 ms intervals and time-aligned with volume information to build a profile of each breath. Heart rate was continuously monitored (TICKR, Wahoo Fitness, Atlanta, GA). Lactate threshold was determined by comparing the points of intersection of the lines of best fit for $\dot{V}O_2$ by time and $\dot{V}O_2$ by $\dot{V}CO_2$ figures (Beaver et al., 1986). The power output observed at 80% LT

was left-shifted by 13.5W to account for the time delay in O_2 delivery to the legs from the lungs and then then divided by the maximum power output to attain the percentage power output achieved at 80% of LT (Keir et al., 2018). For the subsequent exercise interventions (see below) the programming of the cycle ergometer was adjusted to transition from a warm-up baseline value of 20 W to the participants-specific work rate defined above.

Exercise intervention. Female participants completed separate exercise sessions during the FOL and LUT phases of their menstrual cycle, whereas male participants completed the exercise session once. During the exercise intervention, TCD (Neurovision 500M, Neurovision TOC2M; Multigon Industries, Elmsford, CA) was used to measure MCAv and is a technique that has been shown to serve as a valid proxy for a direct measure of CBF (i.e., Xenon tracing) (Bishop et al., 1986; Madsen & Secher, 1999). The TCD probe was coated in an aqueous ultrasound gel (Aquasonic Clear, Parker Laboratories Inc., Fairfield, NJ) and attached to a headband that secured its position over the right temporal window (see also Tari et al., 2020; Shirzad et al., 2022). As per the $\dot{V}O_{2peak}$ assessment, heart rate (HR) was continuously measured during exercise interventions.

All exercise sessions entailed a 10-min baseline (i.e., participants sat on the ergometer without pedaling) followed by a 2-min warm-up at a light intensity (i.e., 20 W) and then a 20 min step transition to the power output corresponding to 80% of participant-specific estimated LT (see Tables 1 and 2). In line with the $\dot{V}O_{2peak}$ assessment, power output during the intervention was independent of pedal cadence which was set at 70 rpm. Following the 20-min intervention, a 2 min cooldown ride was completed at 20 W. As shown in **Figure 3**, TCD data were collected from baseline to the end of the 20 min intervention. The order female participants completed FOL and LUT phase exercise interventions was counterbalanced.


$\dot{V}O_{2peak}$
80% LT
MALE
FEMALE
FOL
LUT

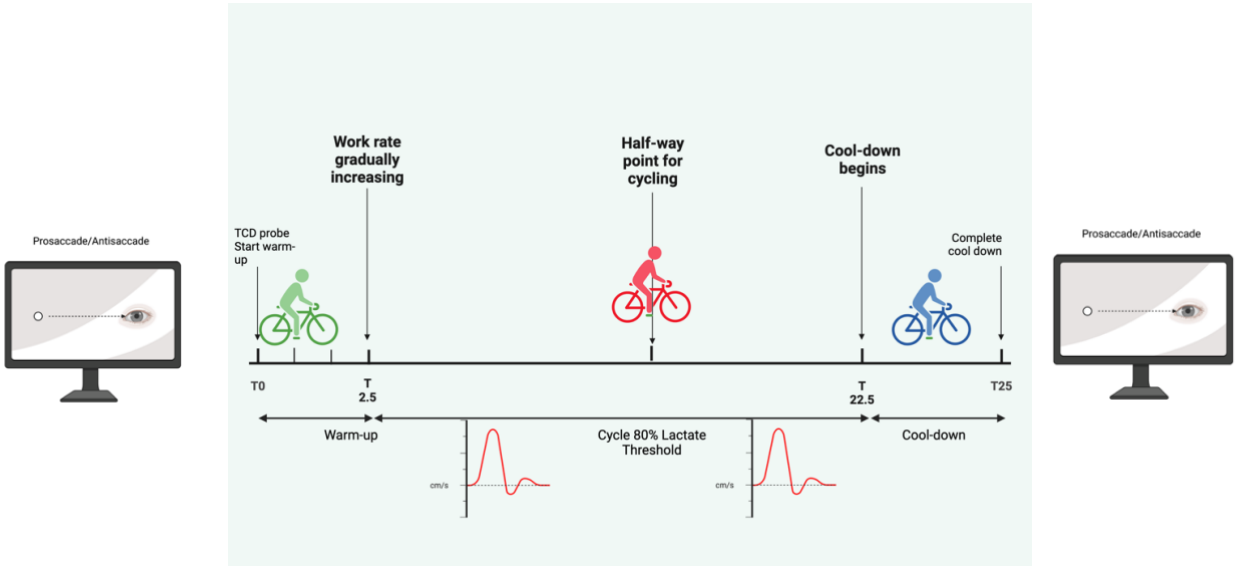

Prosaccade/Antisaccade
TCD probe
Start warm-up
Work rate gradually increasing
Half-way point for cycling
Cool-down begins
Complete cool down
T0
T 2.5
T 22.5
T25
Warm-up
Cycle 80% Lactate Threshold
Cool-down
cm/s
Prosaccade/Antisaccade

Figure 3. Schematic of the experimental sessions performed by male and female participants. All participants performed an initial $\dot{V}O_{2peak}$ test to determine a participant-specific power output for a moderate exercise intensity (i.e., 80% of lactate threshold) in subsequent exercise interventions. Female participants completed separate 20-min exercise session during their follicular and luteal menstrual cycle phases, whereas male participants performed a single session. Prior to and immediately after each session participants completed an assessment of executive function via the pro- and antisaccade task. Transcranial Doppler ultrasound (TCD) was used to measure participant MCAv (middle cerebral artery velocity (cm/s)) during exercise.

Table 1. Female participant-specific and group demographic information and physiological performance variables including estimated lactate threshold (LT) derived from the $\dot{V}O_{2peak}$ task.

Participant	Age (years)	Height (cm)	Weight (kg)	$\dot{V}O_{2peak}$ mL/kg/min	LT mL/min	Watts 80% LT and downshift
1	19	163	57	35.08	1000	73
2	25	165	75	21.33	1010	45
3	25	170	70	30.23	1150	71
4	21	157	70	20.75	790	102
5	20	160	56	26.78	810	76
6	27	155	55	30.90	850	65
7	19	157	50	32.83	840	48
8	21	163	59	45.76	1090	38
9	21	162	57	26.31	969	47
10	21	166	72	29.16	1000	70
11	28	167	72	23.61	784	27
12	25	152	43	30.23	777	43
13	24	152	54	27.77	828	36
14	21	168	58	51.72	900	64
15	21	155	48	39.58	739	28
16	21	180	84	32.14	1770	122
μ	*22*	*162*	*61*	*31.40*	*957*	*60*
(SD)	*(3)*	*(7)*	*(11)*	*(8.41)*	*(248)*	(26)

Table 2. Male participant-specific and group mean demographic information and physiological performance variables including estimated lactate threshold (LT) derived from the $\dot{V}O_{2peak}$ task.

Participant	Age (years)	Height (cm)	Weight (kg)	$\dot{V}O_{2peak}$ mL/kg/min	LT mL/min	Watts 80% LT and downshift
1	23	188	100	31.73	1570	126
2	24	185	86	32.55	1420	35
3	22	170	72	45.83	1400	120
4	26	180	88	36.36	1580	83
5	21	188	80	35.45	1650	99
6	20	172	58	34.13	990	45
7	25	191	82	45.12	1660	93
8	26	177	75	42.66	1650	97
9	26	173	62	45.16	1150	42
10	28	180	75	42.66	1443	97
11	20	181	82	36.58	1360	75
12	23	186	80	33.75	1135	60
13	23	191	88	46.59	1660	98
14	23	183	79	32.91	1207	80
15	24	181	84	41.66	1620	78
16	20	189	82	34.14	1470	117
17	25	174	64	20.31	673	69
18	22	175	64	32.34	960	70
19	22	156	77	44.15	1443	77
20	21	167	59	45.25	1390	76
21	26	152	67	28.35	856	52
μ	*23*	*178*	*76*	*37.40*	*1347*	*80*
(SD)	*(2)*	*(10.62)*	*(11)*	*(7.00)*	*(290)*	*(25)*

2.2.5. Oculomotor assessment

Participants completed an oculomotor assessment before (pre-exercise) and immediately after (postexercise) an exercise session. Participants sat in a height adjustable chair in front of a table and placed their head in a head and chin rest. Participants sat facing a 30-inch LCD monitor (60 Hz, 8-ms response rate, 1280 x 960 pixels; Dell 3007WFP, Round Rock, TX) that was located 550 mm from their head position. The gaze position of participants' left eye was measured via a video-based eyetracker (EyeLink 1000 Plus; SR Research, Ottawa, ON, Canada) sampling at 1000 Hz. Prior to data collection, the lights in the experimental suite were extinguished and the experimenter completed a 9-point calibration of the viewing space followed by a validation (i.e., <1º for any point in the calibration space). All experimental events were controlled via

MATLAB (R2018b; The MathWorks, Natick, MA) and the Psychophysics Toolbox extensions (v 3.0) (Brainard et al., 1997) including the EyeLink Toolbox (Cornelissen et al., 2002). A separate monitor, visible only to the experimenter, provided real-time gaze information (i.e., displacement and velocity) and the accuracy of the eye-tracker (i.e., to perform a recalibration if necessary).

In advance of data collection, an onscreen tutorial provided participants instructions on the nature of pro- (i.e., saccade to veridical target location) and antisaccade (i.e., saccade to a direction opposite to a target) trials. Participants were further instructed that pro- and antisaccades would be completed in separate blocks (the order of which was randomized) and were informed in advance as to the nature of the upcoming block task-type (i.e., pro- or antisaccade). During data collection, visual stimuli were presented on a black screen (0.1 cd/m^2) and included a 1º midline located white fixation cross (127 cd/ m^2) presented at participants eye level and targets (i.e., open white circles; 2.5º in diameter, 127 cd/m^2) presented 15º (i.e., proximal target) and 20º (i.e., distal target) to the left and right of fixation and in the same horizontal plane. Fixation onset cued participants to direct their gaze to its location and once a stable gaze was achieved (i.e., $\pm$1.5º for 450 ms) a uniformly distributed randomized foreperiod (1000-2000 ms) was initiated after which the fixation was extinguished and a target appeared 200 ms thereafter (i.e., gap paradigm). The target remained visible for 50 ms and its onset cued participants to pro- or antisaccade "as quickly and accurately" as possible. Each block of pro- and antisaccades included the random presentation of 20 trials to each visual field (i.e., left and right) and target eccentricity (i.e., proximal, distal) for a total of 80 trials per block. Following the pre-exercise oculomotor assessment, participants immediately began the exercise intervention. The postexercise oculomotor assessment was initiated only after participants heart returned to a value less than 100 bpm (i.e., 2-5 min). Each oculomotor assessment – including calibration – required ~17 min.

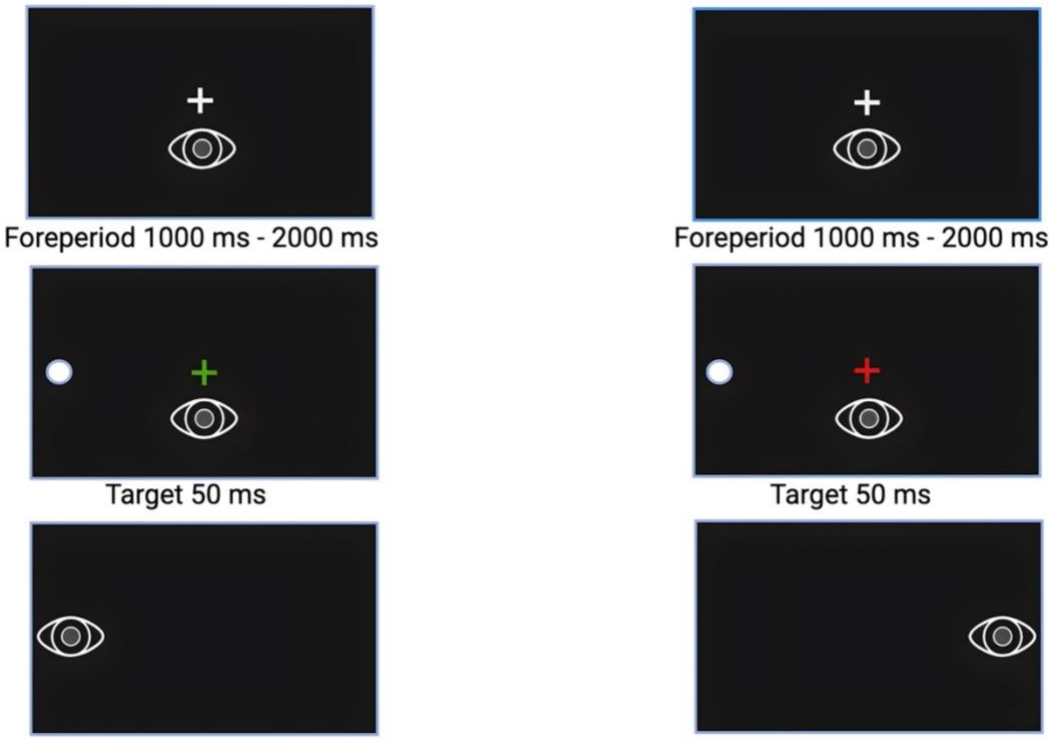


Figure 4. Schematic of the pro- (left) and antisaccade (right) task. For both tasks, a white fixation cross appeared at midline and following a variable foreperiod (1000-2000 ms) the fixation disappeared and 200 ms thereafter a target was presented left or right of fixation for 50 ms (i.e., gap paradigm). Target onset cued participants to pro- or antisaccade "as quickly and accurately" as possible.

2.2.6. Data reduction, dependent variables and statistical analyses

TCD data corrupted by signal aliasing and/or signal loss (e.g., a sudden head shift) were omitted (Terslev et al., 2017) and peak systolic MCAv were retained for analyses because they provide a valid assessment of TCD-based CBF (Clyde et al., 1996; Rosengarten and Kaps, 2001). Peak systolic MCAv were computed during the last-minute of baseline and the last minute of the exercise intervention (i.e., steady state).

For the oculomotor task, point of gaze data were filtered offline via a dual-pass Butterworth filter using a low-pass cutoff frequency of 15 Hz. Saccade onset was determined via velocity, and acceleration values exceeding 30°/s and 8000°/s^2, respectively. Saccade offset was indicated when velocity fell below 30°/s for 40 ms. Trials involving an eye blink or anticipatory response (i.e., RT < 50 ms) were excluded. In addition, trials involving a RT with a standard deviation 2.5 times a participant- and task-specific mean were excluded as were trials with amplitudes less 2° or greater than 30° (Gillen & Heath, 2014b). Less than 9% of trials were

removed for the aforementioned criteria. Trials involving a directional error (i.e., a prosaccade instead of an instructed antisaccade or vice versa) were excluded because they are mediated via planning mechanisms distinct from their correct directional counterparts (DeSimone et al., 2014). Directional errors for pro- and antisaccades were 2% and 8%, respectively, and the low error rate is attributed to their completion in separate blocks. Oculomotor dependent variables include RT (time from response cueing to saccade onset), saccade duration (i.e., time from movement onset to movement offset), and saccade gain variability (i.e., within-participant standard deviation of saccade amplitude/veridical target location.)

Female participants HR and MCAv data were examined via 2 (menstrual phase: FOL, LUT) by 2 (time: baseline, steady state) fully repeated measures ANOVA. Subsequently, and pending the absence of a higher-order interaction involving menstrual phase, female participants' data were collapsed as a function of menstrual phase and contrasted to male participants via 2 (group: female, male) by 2 (time: baseline, steady state) mixed-groups ANOVA. The same procedure was used for oculomotor dependent variables wherein: (1) data for female participants were examined via 2 (menstrual phase: FOL, LUT) by 2 (time: pre-exercise, postexercise) by 2 (task: prosaccade, antisaccade) fully repeated measures ANOVA, and (2) female participants data were collapsed as a function of menstrual phase and contrasted to male participants 2 (group: female, male) by 2 (time: pre-, postexercise) by 2 (task: pro-, antisaccade) mixed-factor ANOVA. Significant interactions were decomposed via simple effects ($p<0.05$) and where appropriate two-sided test statistics we used to determine whether means were within an equivalence boundary (Lakens et al. 2018: Advances in Methods and Practices in Psychological Science)

2.3 Results

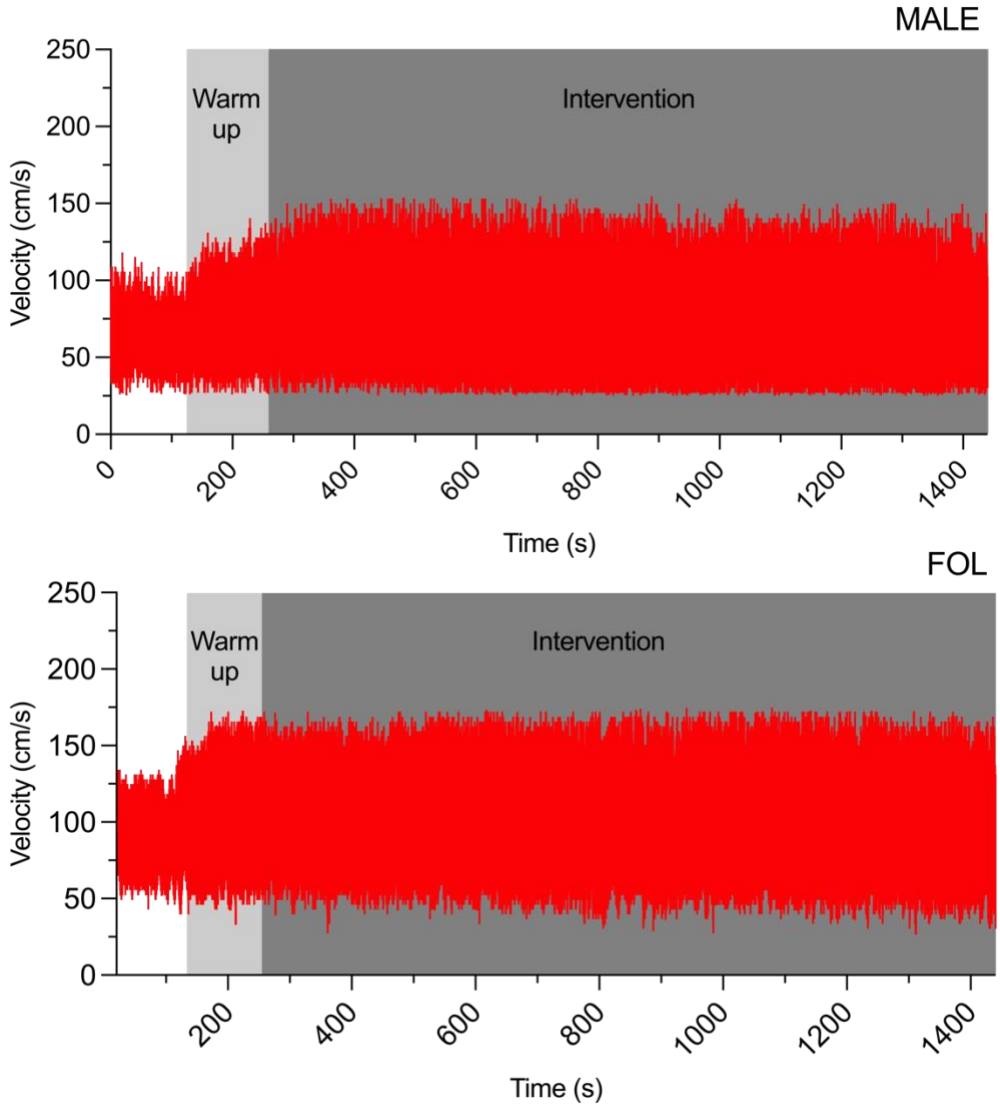
2.3.1 Heart rate and MCAv

Figure 5 shows MCAv continuously across baseline, warm-up and exercise sessions for an exemplar female (separately for FOL and LUT phases) and male participant. The figure provides a qualitative demonstration of an exercise-based increase in CBF for both participants.

FOL and LUT phase comparison. Results yielded main effects for time, $Fs(1,15)=162.12$ and 68.61, for HR and MCAv, respectively, $ps < 0.001$, $\eta_p^2=0.92$ and 0.82, indicating that values increased from baseline (HR: 83 bpm, SD=17, MCAv: 91 cm/s, SD=9) to steady state (HR: 136

bpm, SD=17, 115 cm/s, SD=15). In addition, MCAv produced a main effect for menstrual phase, F(1,15)=9.36, p=0.008, η_p^2=0.38: values were larger in the LUT (112 cm/s, SD=16) than FOL (100 cm/s, SD=16) phase; however, neither HR nor MCAv yielded a reliable time by menstrual phase interaction, Fs(1,15)<1.38, p>0.26, η_p^2<0.06. Thus, FOL and LUT phase HR and MCAv demonstrated a comparable baseline to steady state change (**Figure 6**).

Female and male participant comparison. Results elicited main effects for time, Fs (1,36)=506.01 and 44.53 for HR and MCAv, respectively, ps < 0.001, η_p^2=0.96 and 0.56, indicating that values increased from baseline (HR: 83 bpm, SD=15, MCAv: 90 cm/s, SD=5) to steady state (HR: 137 bpm, SD=15, MCAv: 112 cm/s, SD=21). HR and MCAv did not reveal a main effect of group nor a group by time interaction, Fs(1,36)<1.01, ps>0.42, η_p^2<.02.



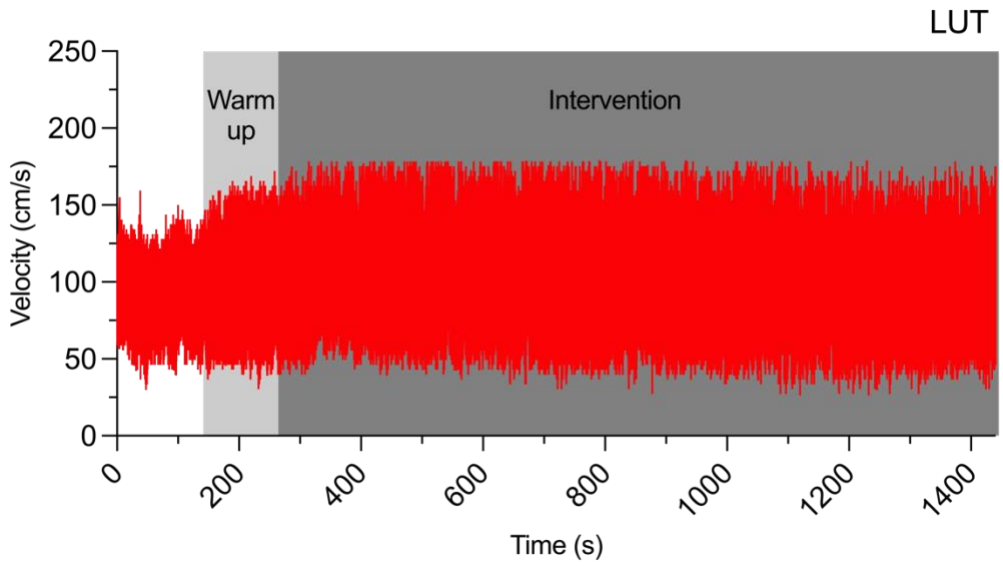


Figure 5. Exemplar participant's male (top panel), and female (bottom panels) middle cerebral artery velocity (MCAv: cm/s) measured with transcranial Doppler ultrasound (TCD). The baseline period is depicted via white space, whereas the 2-min warm-up is depicted by the light gray area, and exercise interventions are depicted via dark gray area. The second panel represents MCAv changes during the follicular phase, whereas the third panel represents MCAv changes during the luteal phase.

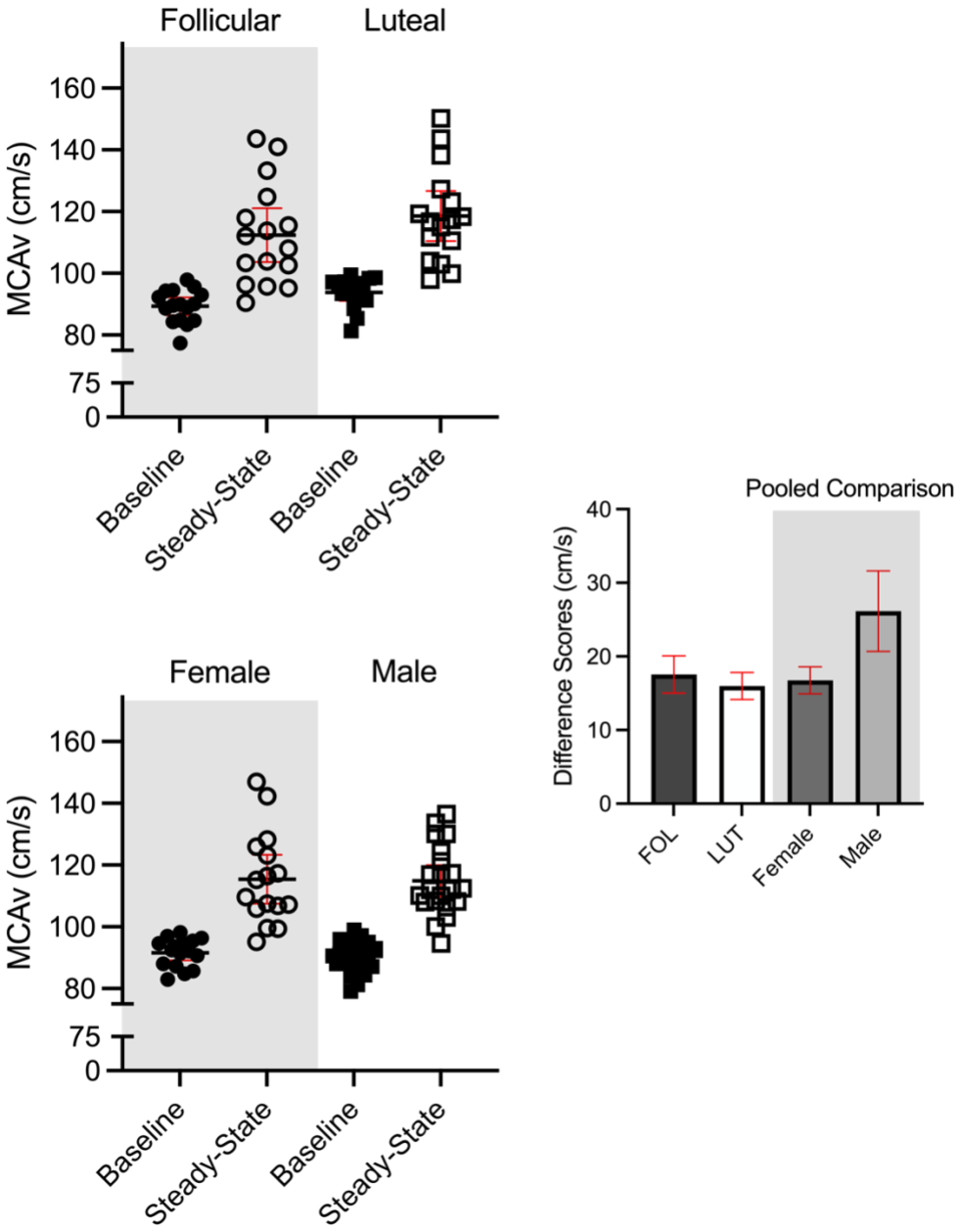


Figure 6. The top left panel shows participant-specific mean middle cerebral artery blood velocity (MCAv: cm/s) for female participants at baseline and steady state during follicular and luteal phase. The bottom left panel shows participant-specific mean MCAv for female (pooled for follicular and luteal phases) and male participants as a function of baseline and steady state. The red line in each the left panels represents the group mean and associated 95% between-participant confidence intervals. The right panel represent group mean difference scores (i.e., steady state minus baseline) and 95% confidence intervals.

2.3.2 Oculomotor assessments: RT, saccade duration and gain variability

FOL and LUT phase comparison. RT data yielded main effects for time, $F(1,15)=19.69$, $p<0.001$, $\eta_p^2=0.57$, task, $Fs(1,15)= 48.19$, $p<0.001$, $\eta_p^2= 0.76$, and their interaction, $F(1,15)=6.03$, $p=0.027$, $\eta_p^2=0.29$. Prosaccade RTs (217 ms, SD=24) were shorter than antisaccades (282 ms, SD=36) and **Figure 7** shows that prosaccade values did not vary from pre- to postexercise ($t(15=0.34$, $p=0.73$, $d_z=0.08$), whereas antisaccade values decreased pre- to postexercise ($t(15)=3.97$, $p=0.001$, $d_z=0.99$). Menstrual phase did not yield a significant main effect, $F(1,15)=2.48$, $p=0.13$, $\eta_p^2=0.14$, nor any higher-order interaction, all $Fs(1,15)<0.70$, $ps>.80$, $\eta_p^2<0.01$. Moreover, and given the primary objective of this work, FOL and LUT phase antisaccade RTs difference scores (i.e., pre-exercise minus postexercise) were examined via a TOST statistic ($d_z=0.75$) and indicated that values were within an equivalence boundary ($t(15)=2.15$, $p=.048$). [1]

Saccade duration and gain variability produced main effects for task, $Fs(1,15)=6.03$ and 7.99, for saccade duration and gain variability, respectively, $p=0.031$ and 0.013, $\eta_p^2=0.30$ and 0.35. Prosaccade durations were shorter (51 ms, SD=6) and endpoints less variable (2.4, SD=0.5) than antisaccades (saccade duration: 56 ms, SD=11, gain variability: 2.9, SD=0.9). Neither variable produced a main effect of menstrual cycle nor any higher-order interaction, all $F(1,14)<1.60$, $p>0.23$, $\eta_p^2<0.10$).

Female and male participant comparison. Results yielded main effects for time, $F(1,35)=7.29$, $p=0.016$, $\eta_p^2=0.17$, task, $F(1,35)= 143.72$, $p=0.016$, $\eta_p^2= 0.80$, and their interaction, $F(1,35)=7.89$, $p=0.008$, $\eta_p^2=0.18$. Prosaccade RTs (210 ms, SD=28) were shorter than antisaccades (276 ms, SD=36), and **Figure 7** shows that prosaccade RTs did not vary from pre- to postexercise ($t(36)=0.44$, $p=0.65$, $d_z=0.07$), whereas antisaccade RTs decreased pre- to postexercise ($t(36)=4.07$, $p<0.001$, $d_z=0.67$). The variable group did not produce a reliable main effect, $F(1,35)=1.79$, $p=0.19$, $\eta_p^2=0.04$, nor any higher-order interactions, $Fs(1,35)<1.23$, $p>.27$, $\eta_p^2<0.03$. Hence, the *magnitude* of the postexercise reduction in antisaccade RTs did not vary across female and male participants.

[1] A Bayesian paired-samples t-test contrasting pooled RTs for FOL and LUT phases produced a BF_{10} value of 0.713. As noted by van Doorn et al.'s. (2021) nomenclature, such a value provides "less than anecdotal evidence" that menstrual cycle status explains RT over the null hypothesis. In fact, the Bayesian value for the null hypothesis ($BF_{01}= 1.403$) indicated that results were more likely under a null model.

Saccade duration and gain variability produced main effects for task, Fs(1,35)=14.47 and 15.39, respectively, ps<0.001, η_p^2=0.30 and 0.31. Prosaccade durations were shorter (52 ms, SD=9) and endpoints less variable (2.5, SD=0.8) than antisaccades (saccade duration: 59 ms, SD=10, gain variability: 3.3, SD=1.2). No other reliable main effects or interactions were observed, Fs(1,35)<1.91, ps>0.17, η_p^2<0.17.

2.3.3 Relationship between MCAv and antisaccade RT difference scores.

Correlation coefficients involving $\dot{V}O_{2peak}$ (see **Tables 1 and 2**) and antisaccade RT difference scores (i.e., pre- minus post-exercise) computed separately for female (collapsed across FOL and LUT phases) and male participants did not reveal a reliable relationship (ps=0.27 and 0.46, for female and male participants, respectively). As well, MCAv differences scores (steady state minus baseline) and antisaccade RT difference scores for female and male participants were not reliably related (ps=0.43 and 0.14).

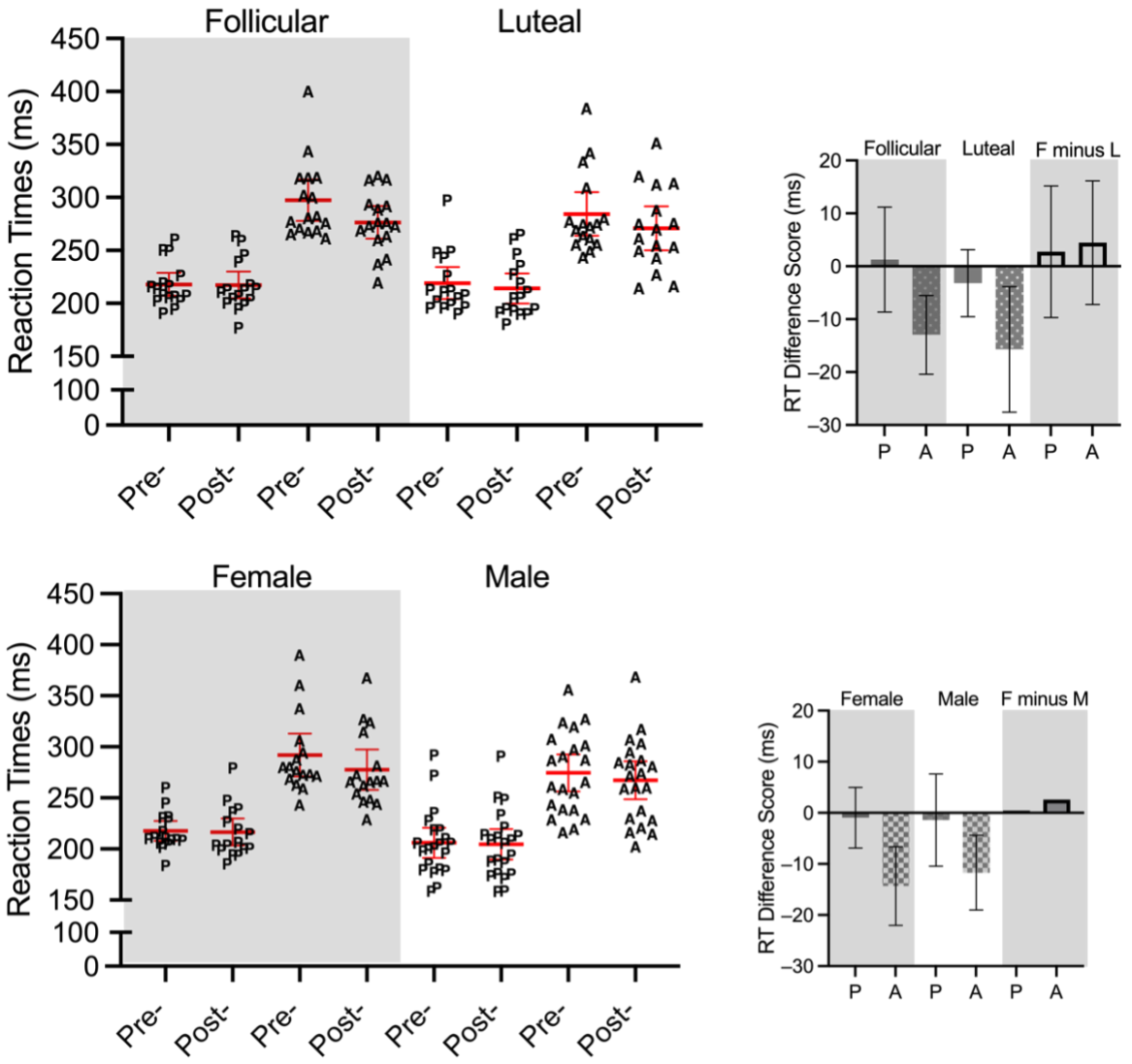


Figure 7. The top left figure shows participant specific pre- and postexercise mean pro- (P) and antisaccade (A) reaction time (RT ms) for female participants as a function of follicular and luteal menstrual phases. The bottom left figure shows participant-specific mean pre- and postexercise pro- and antisaccade RTs for females (gray panel and pooled as function of follicular and luteal phase) and male participants. The top right inset figure shows participant-specific mean pro- and antisaccade RT difference scores (postexercise minus pre-exercise) for follicular (gray panel) and luteal menstrual cycle phases. The bottom right inset figure shows mean pro- and antisaccade RT difference scores (postexercise minus pre-exercise) for female (gray panel) and male participants and the difference, i.e., (female participants minus male participants). The red line in each panel represents group mean values and associated 95% between-participant confidence intervals.

2.4 Discussion

The goals of this investigation were to determine: (1) whether menstrual cycle phase influences exercise-based changes in CBF and the magnitude of a postexercise EF benefit, and (2) whether EF benefits vary between female and male participants. In outlining my findings, I first describe whether a MCAv response to exercise varied as a function of FOL and LUT phases and varied between female and male participants. Subsequently, I discuss FOL and LUT phase postexercise EF changes and associated comparisons between female and male participants.

2.4.1. MCAv changes to exercise across FOL and LUT phases and between female and male participants

Baseline MCAv was greater in the LUT compared to the FOL phase and is a result linked to increased estrogen concentration in the former phase leading to decreased cerebrovascular impedance (Peltonen et al., 2016, Nevo et al., 2007, Ospina et al., 2003, Słopień et al., 2003). Notably, however, LUT and FOL phase showed an equivalent magnitude baseline to steady state increase in MCAv in response to the exercise protocol used here. Although I am unaware of work examining exercise-based changes in MCAv across menstrual cycle phases, work has addressed CBF changes in response to a hypercapnic environment (i.e., higher-than-atmospheric concentration of CO_2). In particular, a hypercapnic environment provides a well-documented increase in CBF via chemoreceptive-induced vasodilation (Hoiland et al., 2019); however, the MCAv response to a hypercapnic environment was observed to be comparable in FOL and LUT phases (Hazlett & Edgell, 2018; Peltonen et al., 2016). Hence, and although the mechanism of the baseline to steady state exercise increase in MCAv observed here is distinct from a hypercapnic environment (Ogoh & Ainslie, 2009), convergent evidence demonstrates that menstrual cycle phases do not influence CBF changes to an environmental stressor.

Female and male participants produced comparable baseline to steady state increases in MCAv. This supports Witte et al.,'s (2019) report that female (FOL phase only) and male participants produced a comparable increase in MCAv in response to moderate intensity aerobic exercise (i.e., 45-55% of HR reserve), and Ashley et al.,'s (2020) observation of comparable MCAv for female (FOL phase only) and male participants throughout a graded exercise test. Accordingly, female and male participants' MCAv response to exercise is comparable across a continuum of exercise intensities even though power output/work rate (see **Tables 1 and 2**) is larger in the latter group (see also Tables 1 and 2 of Ashley et al. and Witte et al., respectively).

2.4.2. Executive function is improved following a single bout of exercise

RTs for prosaccades did not reliably vary from pre- to postexercise. Prosaccade RTs were also shorter than antisaccades regardless of the group and pre- and postexercise manipulations and is an expected finding given their mediation via direct retinotopic projections in the superior colliculus (Pierrot-Deseilligny et al., 1995). In turn, antisaccade RTs were decreased postexercise in FOL and LUT phases and null hypothesis and equivalence tests indicating that the magnitude of this benefit did not vary as a function of menstrual cycle phase. Antisaccade RTs were also shown to produce an equivalent magnitude postexercise reduction between female and male participants. The postexercise reduction in antisaccade RT cannot be attributed to a general improvement in information processing given that antisaccades – but not prosaccades – showed a selective reduction. Moreover, the postexercise antisaccade RT reduction cannot be attributed to a speed-accuracy tradeoff because antisaccade durations and gain variability did not vary from pre- to postexercise. As well, our group has repeatedly shown that the RT change is unrelated to a practice-related performance benefit (e.g., Heath et al., 2018; Petrella et al., 2019; Samani and Heath 2018; Shirzad et al., 2022; Shukla and Heath 2022; Tari et al., 2020; 2021; 2023). Instead, results are in line with an extensive literature reporting that a single bout of exercise provides a selective EF benefit (for meta-analyses see, Chang et al., 2012; Lambourne and Tomprowski, 2010; Ludyga et al., 2016).

Null hypothesis and TOST statistics showed that antisaccade RT difference scores (i.e., postexercise minus pre-exercise) were comparable between the FOL and LUT phases. In other words, the magnitude of the postexercise reduction in antisaccade RT was not affected by menstrual cycle phase. Such a result adds importantly to the literature insomuch as it demonstrates that female participants menstrual cycle status – or knowledge thereof- should not be used as a factor limiting their participation in future research examining exercise-mediated changes to EF or cognition.

One important issue to address is the view that female participants have "improved" EF and visuospatial skills on par to male participants during the FOL phase of their menstrual cycle – a conclusion drawn largely for the mental rotation literature (i.e., performer mentally "rotates" a 3D object until it does – or does not – match and exemplar) (Hampson et al., 2014; Hausmann et al., 2000). Of course, the present work employed a directed measure of EF (i.e., antisaccades) and results demonstrated comparable antisaccade RTs (at pre- and postexercise assessments)

across FOL and LUT phases, and between female and male participants. In other words, results provide no evidence of menstrual cycle- and/or sex-specific differences in a directed measure of EF (see also Bannbers et al., 2012). What is more, the present results are in line with Sundström Poromaa and Gingnell's (2014) review asserting that high-quality studies provide no compelling evidence that menstrual cycle impacts EF or cognition (see also Le al., 2020). A second issue to address is that power output required during the exercise intervention was smaller for female than male participants (see **Tables 1 and 2**). From this it could be argued that exercise intensity was not matched across – or within – participant groups and may have therefore impacted CBF and EF responsiveness to exercise. Recall, however, that power output was prescribed based on 80% of estimated LT, and as such, the prescribed exercise protocol used here represents a study strength ensuring all participants exercised at an intensity matching their individual level of cardiorespiratory fitness (Keir et al., 2018).

2.4.3. Limitations and future directions

I acknowledge that my study is limited by various methodological constraints. First, TCD does not account for changes in MCA diameter. This is a potential limitation because the MCA is capable of dilation and constriction in response to changes in CO_2 concentration (Coverdale et al., 2015). That said, I am unaware of evidence from the literature indicating that MCAv does not provide a valid proxy for CBF-changes to exercise. Second, it could be argued that the fitness level of female participants was less than male participants given the difference in group average $\dot{V}O_{2peak}$ (i.e., female participants = 31.40 mL/kg/min, male participants = 37.40 mL/kg/min). It is, however, important to recognize that Ludyga et al.,'s (2016) meta-analysis reported that both low- and high-fit individuals accrue a comparable magnitude postexercise EF benefit (but see Chang et al., 2012) and the present results showed that there was not a relationship between $\dot{V}O_{2peak}$ and postexercise antisaccade RTs. Third, the absence of a reliable correlation between MCAv and antisaccade difference scores indicates that an exercise-induced increase in CBF was not directly related to a postexercise EF benefit. This is a limitation because it suggests that CBF may be one of a number of mechanisms that mediate an EF benefit. Fourth, the present study did not measure ovarian hormone concentrations across more than one menstrual cycle, therefore it is unclear whether changes in estrogen and/or progesterone relate to the magnitude of a postexercise EF benefit.

2.5 Conclusion

Menstrual cycle status did not influence an exercise-based change in CBF or the magnitude of a postexercise EF benefit. Moreover, female and male participants demonstrated comparable CBF changes to exercise and comparable postexercise EF benefits. These results promote a framework for inclusion in demonstrating that menstrual cycle status should not limit the involvement of female participants in research examining single bout postexercise changes to EF and cognition.

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Appendices

Appendix A: Initial Health Science Research Board Approval

Western Research

Date: 6 January 2022

To: Dr. Matthew Heath

Project ID: 119633

Study Title: Post-exercise executive function and cortical hemodynamics during the different phases of the menstrual cycle

Application Type: HSREB Initial Application

Review Type: Delegated

Full Board Reporting Date: 25/January/2022

Date Approval Issued: 06/Jan/2022

REB Approval Expiry Date: 06/Jan/2023

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 and mandated training must also be obtained prior to the conduct of the study**.

Documents Approved:

Document Name	Document Type	Document Date
PARQPlus 2020	Paper Survey	01/Nov/2019
GLTEQ	Paper Survey	Received January 4, 2022
Clean_Thesis_Research Protocol_Dec17_V6_PP_edit	Protocol	17/Dec/2021
Clean_Recruitment Poster_Thesis_Dec17	Recruitment Materials	17/Dec/2021
Clean_Thesis_Email Script_Dec17	Email Script	17/Dec/2021
Clean_Thesis_LOI_Male_Dec17_V6_PPedit	Written Consent/Assent	17/Dec/2021
Clean_Thesis_LOI_Female_Dec17_V6_PP_edit	Written Consent/Assent	17/Dec/2021

Documents Acknowledged:

Document Name	Document Type	Document Date
Clean_Itemized Study Budget_Dec17	Study budget	17/Dec/2021

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,

Karen Gopaul , Ethics Officer on behalf of Dr. Philip Jones, HSREB Chair

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

Appendix B: Exercise and Physical Fitness Questionnaires

Godin Leisure-Time Exercise Questionnaire (GLTEQ)

Godin Leisure-Time Exercise *Questionnaire*

During a typical **7-Day period** (a week), how many times on the average do you do the following kinds of exercise for **more than 15 minutes** during your free time (write on each line the appropriate number).

Weekly leisure activity score = (9 × Strenuous) + (5 × Moderate) + (3 × Light)

	Times per week		Totals
a) **STRENUOUS EXERCISE (HEART BEATS RAPIDLY)** (e.g., running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling)		**X9**	
b) **MODERATE EXERCISE (NOT EXHAUSTING)** (e.g., fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)		**X5**	
c) **MILD/LIGHT EXERCISE (MINIMAL EFFORT)** (e.g., yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking)		**X3**	
WEEKLY LEISURE-TIME ACTIVITY SCORE			

EXAMPLE
Strenuous = **3** times/wk
Moderate = **6** times/wk
Light = **14** times/wk
Total leisure activity score = (9 × **3**) + (5 × **6**) + (3 × **14**) = 27 + 30 + 42 = 99

Godin Scale Score	Interpretation
24 units or more	Active
14 – 23 units	Moderately Active
Less than 14 units	Insufficiently Active/Sedentary

Adapted from: Godin, G. (2011). The Godin-Shephard leisure-time physical activity questionnaire. Health & Fitness Journal of Canada, 4(1), 18-22.

ONS® Oncology Nursing Society

Physical Activity Readiness Questionnaire (PAR-Q+)

Below is the .pdf link to the PAR-Q+ form used for this dissertation.

2019:

http://eparmedx.com/wp-content/uploads/2013/03/PARQPlus2019ImageVersion1.pdf

Curriculum Vitae

Name:	Priyanka Persaud
Post-secondary Education and Degrees:	Ontario Tech University Oshawa, Ontario, Canada 2015-2020 BSc. Hons. & Mgmt Dean's List (Fall 2015, Winter 2017, Fall 2017, Winter 2018) President's List (Winter 2016, Fall 2016) The University of Western Ontario London, Ontario, Canada 2020-2023 M.Sc. Kinesiology Candidate
Honours and Awards:	Undergraduate Research Award, $2,000 Supervisor Dr. Stephen Jackson, Faculty of Business and Information Technology
Related Work Experience	Teaching Assistant The University of Western Ontario 2020-2023

Publications:

Persaud, P., Heath, M. (2023) Menstrual Cycle Status does not Impact Exercise-Based Changes in Cerebral Blood Flow or Executive Function Benefits. *Psychophysiology.* Manuscript submitted for publication.

Tari, B., Edgar, C., **Persaud, P.,** Dalton, C., & Heath, M. (2022). The unidirectional prosaccade switch-cost: no evidence for the passive dissipation of an oculomotor task-set inertia. *Experimental Brain Research*, *240*(7-8), 2061-2071.

Marshall, S., Gabiazon, R., **Persaud, P.**, & Nagamatsu, L. S. (2023). What do functional neuroimaging studies tell us about the association between falls and cognition in older adults? A systematic review. *Ageing Research Reviews*, 101859.

Conference Presentations:

Priyanka Persaud, Benjamin Tari, Glen Belfry, Matthew Heath. Postexercise executive function and cortical hemodynamics during the different phases of the menstrual cycle. Western Research Forum. London, Ontario.

Persaud, P., Giuffre, L., Edgar, C., & Heath, M. (2022, submitted). Postexercise executive Function & Cortical Hemodynamics During the Different Stages of the Menstrual Cycle. In progress. Cognitive Neuroscience Society, San Francisco CA, United States of America.

At-home tablet-based study of the effects of exercise and mindfulness interventions on executive function. The Southern Ontario Motor Behaviour Symposium. Priyanka Persaud, Matthew Heath. Presented by: Priyanka Persaud