Dual-Task Effects of Concurrently Coupling Aerobic Exercise with Virtual Navigation

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Kinesiology

Waterloo, Ontario, Canada, 2020

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Aerobic exercise is a modifiable lifestyle factor that is important for maintaining or improving both physical health and brain health. Maintaining or improving executive function throughout the lifespan is a prominent area of focus for academic research as the global population ages. Both executive training and aerobic exercise, in and of themselves, have been shown to be means of improving executive function. There has since been a focus on combining exercise and executive challenge to determine if this provides an additive benefit to executive ability. What is often overlooked, however, is how the concurrent exercise-executive challenge effects the outcome of the exercise itself, which is important as improving aerobic capacity is a goal of rehabilitation. Therefore, the purpose of this thesis was to investigate dual-task trade-off effects that occur when concurrently coupling aerobic cycling with a virtual navigation task. The primary aim of this work is to characterize behavioural parameters of both the cycling and navigation tasks, as well as the impact to the physiological parameters of the exercise.

Study 1 was designed to describe the behavioural components of exercise and heart rate with respect to different concurrent executive demands. Study 2 was designed to inform the methodological task considerations of the virtual navigation task(s) that would be used in subsequent studies. Study 3 specifically examined dual-task trade-off effects of virtual navigation coupled with aerobic cycling on navigation performance, cycling cadence and heart rate, while Study 4 extended the work of Study 3 by examining if dual-task trade-off effects would be ameliorated with repeated exposure to the tasks. Overall, the findings of these studies show that young health adults are able to concurrently perform a virtual navigation task with an aerobic challenge, but that the task demands and design will directly impact performance of the exercise and the associated heart rates achieved. Moreover, despite the concurrent challenge being overall more demanding of mental resources, this was the task that the majority of participants found most enjoyable overall. Findings from this thesis provide a basic framework from which other dual-task exercise-executive challenge paradigms can be designed, and can inform task design considerations.

Acknowledgements

To those who graciously volunteered their time to participate in this research, I thank you.

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List of Abbreviations

AD	Alzheimer's Disease
ADLs	Activities of Daily Living
ANOVA	Analysis of Variance
BDNF	Brain Derived Neurotrophic Factor
CVD	Cardiovascular Disease
CYCLE	Cycling Only Task
ECG	Electrocardiography
EEG	Electroencephalography
FITT	Frequency, Intensity, Time, Type
fMRI	Functional Magnetic Resonance Imaging
GAQ	Get Active Questionnaire
HR	Heart Rate
HRR	Heart Rate Reserve
IGF-1	Insulin like Growth Factor 1
LTP	Long Term Potentiation
MCI	Mild Cognitive Impairment
MRI	Magnetic Resonance Imaging
NASA-TLX	NASA Task Load Index
OPA	Occipital Place Area
PAR-Q	Physical Activity Readiness Questionnaire
PFC	Prefrontal Cortex
PPA	Parahippocampal Place Area
RER	Respiratory Exchange Ratio
ROF	Rating of Fatigue

RPE	Rate of Perceived Exertion
RPM	Revolutions Per Minute
RSC	Retrosplenial Cortex
TBI	Traumatic Brain Injury
VAS	Visual Analog Scale
VEGF	Vascular Endothelial Growth Factor
VO_2	Volume of Oxygen Consumption
VR	Virtual Reality
VST	Visual Search Task
VSWM	Visuospatial Working Memory
W	Watts

Chapter 1: Literature Review

1.1 Brain Health

Brain health broadly encompasses the structural and functional integrity of the brain and the resulting behavioural output (Voss et al., 2013). From microscopic, to system, to behavioural levels, brain health includes appropriate regulation of cellular and molecular processes such as the release and regulation of neurotransmitters, short and long-term neuroplastic, neurogenic and angiogenic adaptations and the functions associated with said regulation, such as correct perception, recognition, and action with respect to a stimulus in order to produce the desired goal directed behaviour (Miller & Cohen, 2001; Stillman et al., 2016; Voss et al., 2013).

The determinants of brain health are numerous but one important factor is the link between physical and brain health, as evidenced in part by measures of impaired brain health in those with a sedentary lifestyle (Voss et al., 2013; Wong et al., 2015). Physical exercise is a modifiable lifestyle factor that can be inexpensive, low risk with respect to injury, and does not pose the long-term negative side effects such as those associated with pharmaceutical interventions (Wong et al., 2015). Exercise has positive effects on both physical and brain health, which in turn reduces risks associated with cardiovascular disease (CVD) and other chronic diseases, such as obesity and diabetes, which increase in prevalence as we age (Bolduc et al., 2013; Wong et al., 2015).

It has been estimated that within the next decade, approximately one quarter of the global population will be aged 65 or older (Bherer, 2015). The processes associated with normal aging present challenges to brain health. For example, age-related changes in cerebrovascular function such as reduction in the density of cerebral vessels, introduces changes in brain health (Raz & Rodrigue, 2006). Cerebrovascular endothelial cell function is altered with age, and this is believed to be a contributing factor to the altered cerebral hemodynamics seen with age, which in turn can decrease the integrity of cerebral white matter (Bolduc et al., 2013; Raz & Rodrigue, 2006). With respect to structural and functional integrity of the brain, age related decline commonly observed includes reduction of brain volume, reduction in brain weight, and atrophy of dendritic spines leading to decreased synaptic density (Chapman et al., 2015; Raz & Rodrigue, 2006). Neurologic changes also impact age-related decline in functional brain health. Neuronal atrophy is prevalent with aging, and occurs predominately in the cortex, hippocampus, and cerebellum (Belleville & Bherer, 2012; Chapman et al., 2015). Atrophy to these brain regions is notable, as these regions are important for supporting executive and cognitive functions, spatial functions, and movement coordination (Bates & Wolbers, 2014; Weinstein et al., 2012). These age related effects on the brain are exacerbated in cases of pathological aging, including: mild cognitive impairment (MCI), dementia, Alzheimer's disease (AD) and neurovascular events such as stroke (Mora, 2013; Weinstein et al., 2012) Accompanying the decline in health of the individual with age-related disease are the issues of increased personal, familial, societal and economic burdens that follow the loss of independence in those with cognitive decline (Belleville & Bherer, 2012; Phillips, 2017).

1.1.1 Measures of Brain Function and Health

Cognitive functions enable us to flexibly adapt to our environment and to the stimuli in our environment, and can serve as important markers of brain health (Enriquez-Geppert et al., 2013). Various cognitive tests or composite measures of cognition are used to assess individuals' capacity, and decrements in performance can indicate neuropsychological impairment, neural injury, and cognitive decline (Enriquez-Geppert et al., 2013). These measurements can also be used to track improvement or recovery as a function of time after the onset of injury or disease, or an intervention / rehabilitation protocol. Measures of cognitive function typically include behavioural metrics of performance such as speed, accuracy, and memory recall (Hall & Marteau, 2014). Physiological correlates of behaviour can also be examined by using various brain imaging tools such as electroencephalography (EEG) measures, as well as structural and functional metrics of brain activation from magnetic resonance imaging (MRI) and functional magnetic resonance imaging (fMRI) respectively (Belleville & Bherer, 2012; Hall & Marteau, 2014).

1.2 Executive Function

'Cognitive function' is a widely used term to cover a broad spectrum of information processing. Specifically, cognitive function is defined as the skills that are required for performing tasks of perception, awareness, understanding, learning, memory, judgement and reasoning (Brancucci, 2012). Executive function, is a subset of cognitive function that consists of processes that are considered to be higher order in nature (Diamond, 2013; Miller & Cohen, 2001). Executive functions are generally considered effortful, and enable us to integrate and converge incoming information, compare that information to an internal state, and coordinate the appropriate task output to achieve a specific goal (Diamond, 2013; Miller & Cohen, 2001). Executive functions enable individuals to exert self-control, plan and predict future actions and outcomes, and enable us to execute goal directed behaviour (Etnier & Chang, 2009; Logue & Gould, 2014). Executive functions include:

attention, inhibition, working memory, cognitive flexibility, planning, reasoning, problem solving, judgement and decision making (Diamond, 2013; Logue & Gould, 2014).

1.2.1 Domains of Executive Function

Executive processes perform different roles, yet must also be integrative in order to achieve the appropriate behavioural output. Therefore, while one domain of executive function may dominate a particular task, they do not act in isolation of each other (Diamond, 2013). Various executive processes are summarized in Table 1.1 and discussed below.

Attention is the process that enables us to focus on a specific sub-set of intrinsic and / or extrinsic sensory information and is a biasing of those signals into other cortical areas for more specific information processing (Herrmann & Knight, 2001; Miller & Cohen, 2001). This biasing of afferent information is vital to guiding appropriate goal-directed action or behaviour. In conjunction with biasing certain networks to attend to poignant information, we must also be able to inhibit large amounts of afferent information that is irrelevant to the current task or behaviour (Corbetta & Shulman, 2002; Miller & Cohen, 2001). Inhibition, or response inhibition, is therefore considered a pillar of executive function by many, as it is the ability to appropriately filter and select the task-relevant, but weaker information away from the strong or dominating task-irrelevant information (Diamond, 2013; Miller & Cohen, 2001).

Memory is another executive domain of interest to many researchers in cognitive and aging science as it is affected by aging and neurologic injury. Memory can be subdivided into three categories: long term memory, short term memory and working memory (Baddeley, 2003). Working memory is another executive function (Diamond, 2013). Baddeley poses that working memory is a limited capacity system that transiently maintains and stores information, and that its purpose is to provide an interface between perception, memory, and motor action (Baddeley, 2003). Furthermore, working memory has been defined as the ability to "maintain and manipulate information online in the absence of incoming sensory or motor stimulation" (Corbetta & Shulman, 2002, pg. 205). A sub-set of working memory is that of visuospatial working memory (VSWM) which is important for spatial activities such as spatial navigation (Lövdén et al., 2007; Zimmer, 2008). Visuospatial working memory enables individuals to maintain visual information in working memory during saccadic eye movements and other disruptions to our current visual scene (Blacker et al., 2014). Visuospatial processing has predominately been described in terms of two main pathways: "what" and "where". The "what" pathway is important for object recognition, and is sub-served by what is commonly referred to as the ventral stream, while the "where" pathway is important for spatial localization of objects and is sub-served by what is commonly referred to as the dorsal stream (Kravitz et al., 2011; Zimmer, 2008). The dorsal stream is important for spatial localization and visuospatial working memory as it enables the transformation of visual information from a retinotopic reference frame to egocentric and allocentric reference frames, which will be discussed in section 1.6.1 below (Kravitz et al., 2011).

Perceptual decision making is the process of interpreting afferent information and translating that information into a behavioural outcome (Heekeren et al., 2008). Decision making requires the individual to choose a single option or single course of action from a series of options based on biasing afferent information (Heekeren et al., 2008). This process is also influenced by familiarity with a prior occurrence of the same or similar events, and the outcome of the choice that was made (Heekeren et al., 2008). Therefore, decision making is highly linked to memory processes.

Planning is a broad executive construct and encompasses numerous executive processes, including attention, decision making, memory and metacognitive skills (Das & Heemsbergen, 1983; Tanji & Hoshi, 2001). It can be described as the selection, generation, and execution of a behaviour that requires afferent information from various levels of cognition – from sensory perception to complex executive tasks as well as afferent information regarding ongoing motor output (Das & Heemsbergen, 1983; Tanji & Hoshi, 2001). Arguably, the purpose of planning is to promote the preservation of cognitive and executive resources as well as energy resources required in order to successfully accomplish the goal of the behaviour (Das & Heemsbergen, 1983).

Humans have highly flexible and adaptable behaviour, and this behavioural flexibility requires numerous interrelated executive and cognitive functions distributed across numerous brain regions (Miller & Cohen, 2001). However, our behavioural flexibility comes at the cost of an increased chance for interference of information processing, confusion, error and uncertainty, and can be influenced by numerous environmental and individual factors (Miller & Cohen, 2001).

Table 1.1: Summary of cognitive and executive processes that are discussed in this thesis, including their definitions, and associated brain regions that support their functioning.

Executive Function	Definition	Brain Regions Involved
Attention	Ability to bias a specific sub-set of sensory afference to other cortical areas for further processing[1,4,6]	Prefrontal cortex[2] Intraparietal cortex[4] Superior frontal cortex[4] Temporoparietal cortex[4] Inferior frontal cortex[4]
Cognitive Flexibility	Ability to adjust to new or changing task demands or rules; the ability to change perspectives when approaching a problem or developing a solution[1,7]	Prefrontal cortex[1] Temporoparietal Junction[6] Inferior prefrontal cortex[7]
Decision Making	Ability to bias specific sensory afference, choose a course of action, and produce a behavioural output[7,8]	Orbitofrontal cortex[7] Ventral prefrontal cortex[7] Dorsolateral prefrontal cortex[7,8] Primary somatosensory cortex[8] Lateral intraparietal area[8]
Planning	Ability to select, generate and execute a behaviour in order to successfully accomplish a goal[7,11]	Prefrontal cortex[7] Posterior parietal cortex[7] Orbitofrontal cortex[7]
Response Inhibition	Ability to select the weaker, but task-relevant stimulus over a more dominating, but task-irrelevant stimulus[1,10]	Prefrontal cortex[10] Dorsolateral prefrontal cortex[5] Ventrolateral prefrontal cortex[10] Pre-Supplementary motor area[10] Supplementary motor area[10] Pre-motor cortex[10] Parietal cortex[10] Insula[10]
Visuospatial Working Memory	Ability to maintain and readily manipulate visual and spatial information in the absence of other incoming information[3,9]	Dorsolateral prefrontal cortex[9] Ventrolateral prefrontal cortex[9] Posterior parietal cortex[9] Ventral intraparietal sulcus[9]
Working Memory	Ability to maintain and readily manipulate information in the absence of other incoming information[1,3]	Dorsolateral prefrontal cortex[1,3,5] Inferior parietal cortex[3,5] Hippocampus[5]

[1]Diamond, (2013); [2]Miller & Cohen (2001); [3]Baddeley, (2003); [4]Corbetta & Shulman (2002); [5]Weinstein et al., (2012); [6]Petersen & Posner (2012); [7]Tanji & Hoshi (2001); [8]Heekeren et al., (2008); [9]Zimmer, 2008; [10]Bari & Robbins, (2013); [11]Das & Heemsbergen (1983)

1.3 Factors that Influence Executive Function

Beyond age and disease related changes, there are other factors that influence executive function, including training executive function and its associated physiological and behavioural effects, as well as participation in aerobic exercise. The latter, which links physical and brain health has emerged in the literature as a means to positively influence executive function. While there are other possible influences on executive function and brain health, such as medications, stress, and sleep, the current work is focused on the potential impact of training executive function and the impact of physical exercise. As a result, these two specific factors are addressed below.

1.3.1 Training Executive Function

The most prominent strategy for improving executive function is to implement executive training itself. Training can be informal, such as participating in executively demanding games (e.g. crosswords, card games or Sudoku's) or highly formalized, through interventions described and implemented in scientific research or rehabilitation protocols (Colcombe et al., 2004; Kelly et al., 2014). Executive training involves paradigms that are designed to specifically promote improvement to specific executive and / or cognitive domains (Kelly et al., 2014). Computerized versions of 'brain training' programs or games have become quite popular as a result of claims stating improvements to executive function, and / or amelioration of executive decline, particularly in aging populations (Baniqued et al., 2015). The literature generally supports the notion that executive training will lead to improvements in executive function. These improvements, however, tend to be restricted to tasks that have similar executive requirements to the task(s) trained, with little to no transfer effects to other executive domains or their associated tasks (Binder et al., 2015; Reijnders et al., 2013). Additionally, while executive training leads to improvements in the executive domain trained, as observed from both behavioural and physiological metrics, improvements to real-world performance of executively demanding tasks and activities of daily living (ADLs) do not occur on a consistent basis (Baniqued et al., 2015).

These findings have led to the exploration of multi-domain training and dual-task training. Multi-domain training combines training from multiple cognitive and executive domains or trains multiple executive functions simultaneously. It is proposed that the interaction of numerous executive and cognitive functions will more accurately reflect real-world activities, thus creating an ecologically valid training task (Desjardins-Crepeau et al., 2016). This task may be more likely to promote transfer effects to a broader array of executive and cognitive functions, as well as promoting transfer effects to performance of ADLs (Belleville & Bherer, 2012; Binder et al., 2015). A dual-task paradigm requires maintaining, coordinating and integrating information from two separate tasks, in many cases a motor task combined with an executive task, such as walking and talking (Wong et al., 2015). It is believed that executive-motor training may be more beneficial for promoting more general cognitive benefits, and transfer to improvements in activities of daily living (Lauenroth et al., 2016; Tait et al., 2017).

1.3.2 Physiological & Behavioural Effects of Executive Training

Executive training has also shown to be a means of influencing physiological changes within the brain, as well as changes to behavioural outcomes. Research with human and animal models has shown that environmental enrichment is important for promoting neuroplastic change associated with cognitive function (Shaffer, 2016; Voss et al., 2013). For improvements to executive function to occur, it is essential that tasks contain elements of novelty, cognitive and executive function, and some element of task challenge so as to maintain interest in the task (Shaffer, 2016).

As previously mentioned, aging is generally associated with negative effects to executive and cognitive functions. There is a decline in functional and structural connectivity of neural networks within the brain, as well as a decrement in global measures of cerebral blood flow (Chapman et al., 2015). A review by Belleville & Bherer (2012) discussed the structural and functional changes that are associated with executive training in older adults. Individuals who partook in executive or executive-motor dual-task training showed structural brain plasticity as a result of training; of course the areas of plastic change were dependent on the task(s) used, but regions noted included the hippocampus, nucleus accumbens and the orbitofrontal cortex (Belleville & Bherer, 2012). Functional changes to brain activation have shown that older adults and those in the early stages of MCI have an increase in activation patterns during executively demanding tasks, followed by a decrement in functional brain activation as cognitive impairment worsens, or as the individual progresses to AD (Belleville & Bherer, 2012).

It has been suggested that executive training may also promote an increase in neurotransmitter receptor concentration, increase the rate of turnover of cellular enzymes, proteins, and lipids, thus improving executive performance due to the increased energy and blood supply demands to the brain (Chapman et al., 2015). This has been revealed by a 12 week intervention demonstrating an increase in global cerebral blood flow for those in the executive training group compared to a control group (Chapman et al., 2015). These increases occurred in the inferior temporal gyrus, precuneus and cingulate gyrus at the 6 week mark, and were higher in the left middle temporal, left superior medial, and left inferior frontal gyri at the 12 week mark, when compared to the control group. It was also found that functional connectivity increased from baseline to 12 weeks in the default mode network and the central executive network, networks whose regions mirrored the areas of increased cerebral blood flow (Chapman et al., 2015). Lastly, the executive training group saw improvements to executive function in two domains when compared to the control group: strategic reasoning and concept abstraction. The authors attribute these changes to the "lengthy language-based materials as well as rich visual stimuli where participants were required to construct novel and abstract interpretations" (Chapman et al, 2015, pg. 404), and suggest future work examine multiple aspects of neuroplastic and behavioural change with respect to executive training (Chapman et al., 2015).

1.3.3 Aerobic Exercise Training

Interestingly, participation in physical exercise has emerged in the literature as another, robust means for influencing executive function. Aerobic exercise, specifically, has been shown to maintain or improve measures of executive function across the lifespan (Bolduc et al., 2013; Hillman et al., 2012; Weinstein et al., 2012). Increased fitness levels mitigate or alleviate many of the negative side effects of CVD, which may in turn mitigate the negative vascular changes observed in the brain, particularly as we age (Raz & Rodrigue, 2006). Colcombe and colleagues (2003) were the first to demonstrate that cardiovascular fitness was associated with higher cerebral tissue density. In a sample of high functioning, healthy older adults aged 55-79, those with a higher level of cardiovascular fitness showed sparing effects in the prefrontal, superior parietal and temporal cortices; areas that are known to atrophy with age (Colcombe et al., 2003).

Increased cardiovascular fitness was also associated with reduced age-related tissue density loss in the anterior and transverse white matter tracts (Colcombe et al., 2003). Colcombe et al. (2003) acknowledged that it was possible that this interpretation could be reversed; that older adults with less cerebral atrophy were better able to maintain a physically active lifestyle. To address this issue, they performed a subsequent study in which they examined the effects of a six month intervention comparing an aerobic walking program to a stretching and toning control group. The older adults in the aerobic walking program showed an increase in brain volume, with the frontal lobes showing the most prominent change, when compared to older adults assigned to the stretching and toning program (Colcombe et al., 2006). Therefore, engaging in an aerobic exercise program, even if started among sedentary older adults, appears to promote positive changes to brain health.

1.4 Physiological & Behavioural Effects of Physical Exercise

In addition the aforementioned benefits of exercise and fitness to brain health, exercise is a low cost and effective way to prevent or reverse the effects of some chronic diseases, including CVD and type II Diabetes (Kramer & Erickson, 2007). Additionally, exercise promotes social interaction and does not pose negative long term side effects of participation, such as those seen with pharmacological interventions (Kramer & Erickson, 2007). Aerobic exercise has robust positive effects on various organs and organ systems throughout the body.

1.4.1 Exercise Effects on the Cardiovascular System

Regular participation in aerobic exercise promotes positive functional and structural adaptations throughout the cardiovascular system. Resting heart rate decreases, as does heart rate at submaximal and maximal work rates when compared to values measured prior to starting an aerobic training program (Rivera-Brown & Frontera, 2012; Wilson et al., 2016). Stroke volume increases at rest, submaximal and maximal exercise as well (Rivera-Brown & Frontera, 2012; Wilson et al., 2016). Increased stroke volume results from the associated increase in myocardial contractility following aerobic exercise training, thus increasing the body's systemic transport of oxygen (Boström et al., 2013; Wilson et al., 2016).

Structurally, the heart undergoes cardiac hypertrophy, resulting in increased cardiac mass, increased size of the cardiac chambers, and an increase in cardiomyocyte size (Boström et al., 2013; Rivera-Brown & Frontera, 2012; Wilson et al., 2016). Furthermore, prolonged aerobic exercise participation promotes an increase in both plasma and total blood volume as well as systemic angiogenesis (Wilson et al., 2016).

The endothelium is a potent moderator of vascular adaptations seen in response to aerobic exercise (Wilson et al., 2016). The endothelium produces and releases various vasoactive hormones that target the vasculature, the most prominent of which is nitric oxide (Wilson et al., 2016). Nitric oxide relaxes vascular smooth muscle, promoting vasodilation, and also plays a protective role against atherosclerosis and thrombolytic events (Wilson et al., 2016). Repeated stress to the vasculature and endothelium with aerobic exercise promotes positive adaptations to the vasculature in a systemic manner, not solely to the vasculature in the muscles required to perform the exercise (Wilson et al., 2016). Thus, aerobic exercise is an important component of a healthy lifestyle for enhancing cardiovascular function and health, and consequently avoiding or mitigating the risk and consequence of cardiovascular disease.

1.4.2 Exercise Effects on the Musculoskeletal System

Regular participation in aerobic exercise increases skeletal muscle's capacity to utilize oxygen primarily due to increased mitochondrial concentration and mitochondrial enzyme concentrations (Heinonen et al., 2014). Aerobic exercise promotes angiogenesis in the active muscle group(s) leading to increased capillary density, in turn increasing oxygen extraction to muscles and resultant oxidative respiration (Heinonen et al., 2014; Rivera-Brown & Frontera, 2012). The mechanical stress of the exercise strengthens bone by maintaining or increasing bone density (Heinonen et al., 2014). It has also been postulated that bone marrow perfusion is enhanced with exercise, possibly promoting the release of stem cells from bone marrow which may further contribute to the exercise induced organ specific adaptations observed elsewhere in the body (Heinonen et al., 2014).

Aerobic exercise promotes lipolysis from fat stores, releasing free fatty acids into the blood stream to be used as an energy source by other tissues. This leads to a reduction in fat mass and a reduction in the size of fat cells, thus improving overall body composition measures (Heinonen et al., 2014). Taken together, with the aforementioned changes to the cardiovascular system, aerobic exercise participation leads to numerous systemic physiological adaptations, which benefit the physical health of the individual.

1.4.3 Exercise Effects on the Brain

As noted above, there is an abundance of literature to suggest that participation in aerobic exercise has positive impacts to brain function as well as other body systems. Many studies have demonstrated that even a single session of aerobic exercise can promote transient changes in brain function. These positive influences have been reported for both physiological and behavioural indices of brain function (Chang, et al., 2012; Chang et al., 2014). The literature has reported that aerobic exercise can improve various aspects of executive function, including inhibition, attention, speed of processing and memory (Chang, et al., 2012; Chang et al., 2014). The majority of research suggests that these higher order executive functions appear to be the most susceptible to a single bout of aerobic exercise (Ludyga et al., 2016). Findings further suggest that these transient improvements to executive function persist anywhere from 20-60 minutes after the cessation of exercise (Ludyga et al., 2016).

Exercise has the ability to influence brain health at the microscopic, functional system, and the behavioural levels. Stillman et al. (2016) proposed a three-tiered model of the interactions between exercise and executive function and the interplay between these two processes. The first tier constitutes molecular and cellular mechanisms (Stillman et al., 2016). Animal models have consistently demonstrated increased neurotransmitter concentrations and the upregulation of neurotrophins and neural signaling molecules (Cassilhas et al., 2016; Cotman et al, 2007; Voss et al., 2013). Key growth factors include: brain derived neurotrophic factor (BDNF), insulin like growth factor-1 (IGF-1), vascular endothelial growth factor (VEGF), serotonin, dopamine, and lactate, as well as their respective signaling cascades (Cassilhas et al., 2016; Cotman et al, 2007; Magistretti & Allaman, 2018; Voss et al., 2013). Various studies with animal models have demonstrated exercise induced increases in gene and protein expressions of both BDNF and IGF-1 (Cassilhas et al., 2016; Stillman et al., 2016). These changes have been observed in numerous brain regions, with the hippocampus showing the most robust and sustaining adaptation (Cassilhas et al., 2016; Stillman et al., 2016). These growth factors promote processes of synaptic plasticity, neuroplasticity, long term potentiation (LTP) and angiogenesis (Stillman et al., 2016; Voss et al., 2013). Benefits to executive function may result from improvement in neuronal functioning by way of neurogenesis, plasticity and neurovascular coupling as these processes promote structural and functional brain changes (Anderson-Hanley et al., 2012; Stillman et al., 2016; Voss et al., 2013).

Structural and functional brain changes are the second tier of Stillman et al.'s (2016) model and examine changes to grey and white matter, functional connectivity, and the resultant effects on executive function (Stillman et al., 2016). The adult human brain has shown the ability to undergo neuroplastic change. For example, hippocampal neurogenesis occurs throughout the lifespan and can effect both brain structure and function as new neurons are generated and integrated into existing networks (Belleville & Bherer, 2012; Kempermann et al., 2010; Voss et al., 2013). It has been postulated that aerobic exercise induced neurogenesis occurs as a dual process: that the aerobic exercise promotes the induction of precursor cells that support neurogenesis and neuroplasticity (BDNF, IGF-1 & VEGF) while environmental enrichment or executive training promotes the survival and integration of these new neurons into the existing networks (Kempermann et al., 2010).

Alterations to brain structure and function at the cellular, molecular, and systems levels, occur through various mechanisms, and these mechanisms converge to ultimately support changes at a behavioural level (Cotman & Berchtold, 2002). The third tier of Stillman et al.'s (2016) brain health model consists of behavioural and social changes that result from, or because of, participation in exercise. The authors discuss the positive effects of exercise on sleep quality, pain relief, stress reduction, and improvement in overall mood (Stillman et al., 2016). The positive changes that occur because of aerobic exercise encourage adherence and thus further, sustained participation in aerobic exercise.

1.5 Combining Exercise & Executive Training

Exercise has been shown to improve executive function across the lifespan. School aged children who are more active tend to have better educational outcomes, and research has shown improvements to both behavioural and neuropsychological metrics of executive function within this age group (Hillman et al., 2012). Exercise has also been shown to improve executive control in older adults, both healthy and those who have begun to experience cognitive decline (Tait et al., 2017). As previously discussed, engagement in executive training or other mentally stimulating activities also demonstrate the potential to improve executive function (Tait et al., 2017). Therefore, what has recently become of interest within the scientific community is the possibility of combining both exercise and executive training, and resultant effects to brain health.

Exercise leads to the production and release of numerous neurotrophic factors and neurotransmitters that facilitate processes of neuroplasticity and neurogenesis (Fabel et al., 2009; Voss et al., 2013). Executive training can be thought of as being analogous to environmental enrichment, thus promoting the integration of the new neurons into the structural areas responsible for producing the desired behavioural output (Voss et al., 2013). Therefore, exercise promotes an environment that can facilitate neuroplastic change while the executive training promotes this use-dependent adaptation (Fabel et al., 2009). This theoretical framework has potential implications for exercise prescription, therapeutic recreation programs for older adults, or for rehabilitation programs for those with MCI, dementia, AD, stroke or traumatic brain injury (TBI).

1.5.1 Nature of Coupling

There are a variety of ways in which aerobic exercise and executive training could be combined into a training session. The scientific literature has examined the nature of combining exercise and executive challenges in two broad categories: sequential training regimes and concurrent training regimes.

A review by Tait et al., (2017) examined the influence of sequential vs. concurrent dual-task exercise training paradigms and the resultant effects to executive function in older adults. With respect to sequential training, they found the potential for an additive benefit to executive function somewhat lacking, and raise numerous causes for concern with respect to sequential training. If the executive training was performed prior to the exercise training, then no benefits to executive function occurred. If the exercise was performed *prior* to the executive training, then benefits to executive function were more likely to occur (Tait et al., 2017). Therefore, the order of exercise and executive training is important. Another issue with sequential training is the difference in overall training volume, as it is not comparable between the three groups of 1) exercise & executive training, 2) exercise only training, and 3) executive only training. The implication is that the benefits of the combined paradigm over the single intervention paradigms may be solely due to the increased volume of training hours (Tait et al., 2017).

While concurrent exercise-executive training has been found to lead to improvements in executive function and overall cognitive function, there is currently a lack of scientific literature to determine if a concurrent training program is more beneficial than either exercise or executive training alone (Tait et al., 2017). This review also suggests that the executive task used in concurrent paradigms engage multiple executive processes (inhibition, attention, planning and working memory) as this appears to offer more global benefits when combined with exercise, as compared to a domain-specific executive task (Tait et al., 2017).

The possible benefits of concurrently combining exercise and executive challenges includes: increased interest and therefore better adherence to exercise on the part of the participant, more time in rehabilitation sessions to focus on other necessary aspects of rehabilitation, and the potential for an additive benefit to executive function, surpassing benefits arising from participating in exercise or executive training alone (Fabel et al., 2009; Kühn et al., 2014). Therefore, this thesis will limit the discussion to examining concurrent training paradigms.

1.5.2 Evidence for Concurrent Training

There has been a paradigm shift that has led to the promotion and popularity of computer / videogame based exercise regimes performed in clinical settings and at home (O'Leary et al., 2011). This has been termed 'exergaming' by some research groups, and enables individuals to use physical exercise or movement to interact with computer simulated virtual environments or games (Anderson-Hanley et al., 2012). It has been suggested that exergames promote participation in physical exercise due to their interactive nature, and provide motivation and adherence due to novelty, competition and variety (Anderson-Hanley et al., 2012; Kühn et al., 2014). These exergames are generally implemented with videogame systems such as Nintendo Wii™, Wii Fit™, Microsoft Kinect™, and Dance Dance Revolution® (Ogawa, et al., 2016)

O'Leary et al. (2011) examined behavioural and neuroelectric measures of inhibitory control after single bouts of videogame play, aerobic exercise, and exergaming in young healthy adults aged 18-25. Videogame play was comprised of seated game play using MarioKart®, aerobic exercise was comprised of treadmill walking at 60% HR_{max} as determined from VO_{2max} testing, and exergaming was comprised various physically active games using Nintendo Wii Fit™ (O'Leary et al., 2011). A resting control condition was also included. A modified Flanker task was used to assess changes to brain function. They found that a single session of moderate intensity treadmill walking led to increased P3 amplitude and decreased response time interference, while the exergaming and videogame play did not modulate behavioural or neuroelectric indices of executive control (O'Leary et al., 2011). There were no significant differences in heart rate between the treadmill walking and the exergame conditions, and both of those active conditions had significantly higher heart rates than seated rest, or seated videogame play (O'Leary et al., 2011).

Exergaming is by no means limited to traditional use of videogames or computer interface systems. Another method of concurrently combining aerobic exercise with an executive challenge is by coupling traditional exercise equipment with a virtual environment. Anderson-Hanley et al. (2012) examined differences between traditional stationary cycling with 'cyber-cycling', in which stationary cycling was combined with virtual on-screen tours or games. Two groups of older adults were trained to monitor heart rate and were to exercise at 60% of their heart rate reserve (HRR); one group participated in the cyber-cycling condition, while the other group performed cycling alone. Those in the cyber-cycle condition had a one month familiarization period prior to the introduction of the virtual tour program (Anderson-Hanley et al., 2012). The authors suggested that the concurrent exercise and executive activity promoted greater executive benefit than exercise alone, as those in the cyber-cycle group showed an increase in performance on both the Colour Trails Difference and the Stroop tasks, while those in the control group showed no change when compared to baseline measures. Additionally, participants in the cyber-cycle group maintained performance on the Digits Backwards task while those in the control group declined over the intervention period (Anderson-Hanley et al., 2012). The authors characterized the sample of participants with respect to what they deem typical diagnostic criteria for MCI, both pre and post intervention. The cyber-cycle group appeared to show a beneficial effect of the concurrent physical and executive challenge, as fewer participants in the cyber-cycle group declined to MCI status after the three month intervention compared to the cycling only group (Anderson-Hanley et al., 2012). Anderson-Hanley et al. (2014) conducted a follow-up study with these participants to further explore the relationship between exercise behaviour, executive function and measures of self-regulation. The authors discuss that individuals with better executive function may be more likely to self-motivate and adhere to maintaining a physically active lifestyle (Anderson-Hanley et al., 2014). Participants from the aforementioned study were invited to continue to participate in what researchers termed 'naturalistic' exercise, five days a week using the cyber-cycle for an additional six months (Anderson-Hanley et al., 2014). They compared the subsample of those who participated in this naturalistic window to those who completed only the original study protocol. Interestingly, they found a negative relationship between executive function improvement and exercise adherence; those who had a declining trend in their executive function after the initial three month intervention were more likely to partake in exercise in the naturalistic window (Anderson-Hanley et al., 2014). The authors suggest that because participants received information regarding the potential benefits of exercise to executive function, and since participants were potentially experiencing declines in their own abilities and ADLs, they may have been more motivated to continue with the exercise-executive training program (Anderson-Hanley et al., 2014).

Barcelos et al. (2015) examined different demands of executive challenge required for virtual navigation, and the associated influence to executive outcomes in older adults (mean age 82 years) when virtual navigation was performed concurrently with exercise. Participants were randomized between two exercise groups, both using stationary cycling. One group exercised and concurrently travelled along a pre-constructed a virtual bike path (considered low executive demand) while the other group travelled through a virtual landscape and were instructed to collect coloured coins and corresponding coloured dragons (considered high executive demand) (Barcelos et al., 2015). This study found that performance measures of the Colour Trails Ratio and the Stroop Ratio showed greater improvement for those in the high executive demand condition when compared to the low executive demand condition after both a single bout of exercise and after a three month intervention period (Barcelos et al., 2015).

1.5.3 Challenges to Concurrent Coupling of Exercise & Executive Training

The potential, as highlighted by Anderson and colleagues (2012), of using an exercise program that concurrently engages executive function, provides an attractive approach to potentially maximize the benefits of exercise. However, concurrently coupling aerobic exercise with an executive training task poses numerous challenges. First, one must consider the type of aerobic exercise to implement as part of a concurrent paradigm. If a goal of research in this field is to enable individuals to partake in this training paradigm either at home, or in a therapeutic setting, then it is important to use commonly available equipment: treadmills, ellipticals, stationary bikes, and steppers. In addition, the selection of the exercise also has implications to the executive demands required for movement and the potential challenge of dual-tasking. For example, as noted below, walking has a greater executive control demand than recumbent cycling due to the additional challenges of dynamic balance control and foot placement (Nagamatsu et al., 2011). There is also much ambiguity regarding which type of executive task to couple with the exercise. There are numerous executive and cognitive training tasks implemented clinically, or used in scientific research, but it has yet to be determined which are best suited to concurrently couple with aerobic exercise. The challenge of executive task selection is twofold: 1) selecting a task with the ability to control task challenge so as not to impose too great a dual- task demand and, 2) selecting an executive task that integrates with the exercise movement so as minimize executive-motor task interference. The executive task should also encompass more than one executive domain to promote the potential for transfer effects to other domains, and potentially to ADLs (Kelly et al., 2014; Marusic et al., 2018). As noted, it is critically important that the concurrent coupling of an aerobic and executive challenge is set at an appropriate level of difficulty; not so easy that individuals disengage with the task(s) and become distracted, but not so difficult so as to demand excessive executive resources, thus increasing stress and frustration and decreasing enjoyment (Van Cutsem et al., 2017).

1.6 Navigation as an Executive Training Task

Regarding the selection of an executive task to couple with exercise, this thesis proposes the implementation of virtual navigation. The proposal of virtual navigation as an executive training task arises from two main aspects: 1) navigation, while being predominately sub-served by the hippocampus also requires the interaction of numerous executive domains, thus increasing the possibility for improvements to numerous executive functions and ADLs, and 2) navigation has natural links to mobility (e.g. walking, cycling). Physically moving through the environment activates specialized neurons in the hippocampus and entorhinal cortex to code for spatial locations in the environment (Moser et al., 2015). While navigation is predominately a hippocampal function, our ability to achieve a desired goal requires interaction between executive functions. For example, we must attend to relevant features of the environment in order to extract salient buildings or landmarks to encode in visuospatial working memory in order to store and recall the route at a later point in time if necessary. It is helpful if these salient environmental features are attended to at decision points along the route such as turns or changes in direction (Lövdén et al., 2007; Wiener et al., 2009). Decision making and planning are executive functions that may interact with each other in order to avoid specific obstacles, develop detour plans as they arise, and to comply with the rules or changing rules of the task itself (Lövdén et al., 2007; Wiener et al., 2009). Therefore, the use of a virtual navigation task coupled with aerobic cycling may more closely mimic the physical and executive demands that are required when moving through an actual environment, and may promote improvement to activities of daily living (Tait et al., 2017).

Additional support for concurrently coupling aerobic exercise with a virtual navigation task comes from the aforementioned studies by Anderson-Hanley et al. (2012, 2014) and Barcelos et al. (2015). Both of these research groups have implemented concurrent aerobic cycling with a virtual navigation game in older adult populations with participants in those studies having the capacity to complete the tasks, and with some improvements to measures of executive function. This prior research further supports the notion of this thesis that virtual navigation is a viable task to couple to exercise.

1.6.1 Brain Regions Involved in Navigation

Navigation is supported by various brain regions and by neurons with highly specified functions. At the cellular level, neurons that have been shown to support spatial navigation include: 1) place cells, which encode for distance and direction of target locations, 2) grid cells, which fire in a hexagonal pattern in order to represent the structure of space, 3) border cells, which code for boundaries within an environment, and 4) head direction cells, which code for the orientation of the head or heading within the environment (Epstein et al., 2017; Moser et al., 2014). Place cells are located within the hippocampus, a structure that is well known to support spatial navigation and long term memory (Moser et al., 2015). The medial entorhinal cortex and parahippocampal region also house grid cells and head direction cells, while head direction cells have also been located in numerous cortical and subcortical regions including the parahippocampal region and the anterior thalamus (Epstein et al., 2017; Moser et al., 2014).

Research had demonstrated three neural networks important for landmark based navigation: 1) the parahippocampal place area (PPA), 2) the retrosplenial cortex (RSC) and, 3) the occipital place area (OPA) (Epstein et al., 2017; Epstein & Vass, 2014). The PPA is more active when viewing environmental related stimuli (buildings, streets etc.) as compared to non-environmental stimuli, and has also shown to be more active to objects that are perceived to be stable within their environments thus promoting their use as a landmark (Epstein et al., 2017; Epstein & Vass, 2014). The RSC is important for determining spatial location and orientation within a larger environment, and the OPA has been shown to be particularly important for determining environmental boundaries and constraints to navigation within the current environment (Epstein et al., 2017; Epstein & Vass, 2014).

The prefrontal cortex (PFC) is an area that supports navigation by interacting with executive functions, and enabling flexible behaviour in order to achieve a desired goal. Research has demonstrated that forcing participants to stray from their planned route and detour to a target location increases the activity in the PFC, suggesting its role in adapting to new environmental constraints (Spiers & Gilbert, 2015). Taken together, successful navigation is dependent on various cortical and subcortical regions.

How humans utilize this information had also been examined extensively in the literature. Navigation is sub-served by two spatial reference systems: egocentric and allocentric reference frames. Egocentric reference frames encode locations with respect to the observer (Wolbers & Wiener, 2014). Within this coordinate system, the observer is the origin and orientation is determined based on the observer's heading within the environment (Wolbers & Wiener, 2014). There are multiple egocentric reference frames coded for in the brain, including eye-centered, head-centered and trunk centered (Wolbers & Wiener, 2014). Egocentric position changes constantly as we move through an environment, and therefore must be updated on a continuous basis. This is referred to as spatial updating and is vital to our ability to navigate complex environments without getting lost (Wolbers et al., 2008). In contrast, allocentric reference frames encode locations of objects with respect to other objects, and are therefore independent of observer motion within the environment (Wolbers & Wiener, 2014).

1.6.2 Executive Demands of Navigation

The ability to navigate between locations is arguably one of the most important applications of spatial cognition (Wiener et al., 2009; Wolbers & Hegarty, 2010). Human navigation can vary greatly in terms of environment; being outdoors in familiar or unfamiliar places, finding a specific room within a building, or navigating through a virtual environment (Wiener et al., 2009; Wolbers & Hegarty, 2010). Human navigation can also vary in terms of context, for example planning a route to traverse between destinations versus unplanned exploration of a place or route between places (Wiener et al., 2009).

Spatial attention, visuospatial working memory and control of eye movements to support spatial awareness are supported by the parieto-prefontal pathway which provides inputs to the PFC from the lateral and ventral intraparietal regions and the middle and medial superior temporal regions (Brunyé, 2018; Kravitz et al., 2011). Engaging in visually guided motor action and integration of object information is carried out by the parieto-premotor pathway which carries information from visual and somatosensory areas to the dorsal and ventral premotor cortices (Brunyé, 2018; Kravitz et al., 2011). Environmental space, distance, heading direction and optic flow are supported by the parieto-medial temporal pathway, which projects to the medial temporal lobe from the caudal inferior parietal lobe, the RSC, the hippocampus and parahippocampus (Brunyé, 2018; Kravitz et al., 2011).

Due to environmental variations and numerous complexities associated with spatial navigation, multiple cognitive and executive resources are required. Individuals must process numerous environmental perceptive cues, attend to specific stimuli while inhibiting other stimuli, avoid obstacles, recall the navigational rules of the environment (for example the motor vehicle rules of the area), and employ problem solving and decision making in order to compute appropriate motor sequencing regarding which way to move (Lövdén et al., 2007; Wiener et al., 2009).

1.6.3 Links to Locomotor Activity

Knowledge of our spatial position and orientation within our environment is an essential everyday function that relies upon a variety of cognitive and executive functions (Bates & Wolbers, 2014; Lövdén et al., 2007; Spiers & Maguire, 2008). Navigation itself is considered a two part process: it involves the processes of locomotion and wayfinding (Wiener et al., 2009). Wayfinding can be defined as the process of selecting and following a route from a point of origin to a destination; this process is then integrated with the body motion that occurs during locomotion to become navigation (Wiener et al., 2009). Research exploring human representation and utilization of large scale space has suggested two main strategies to support navigation: 1) route knowledge: knowing direction, and which turns to make at different locations and landmarks, and 2) survey knowledge: an integrated representation of the spatial relationship between locations and landmarks, which is often referred to as a cognitive map (Lövdén et al., 2007; Spiers & Maguire, 2008). Survey knowledge is important for us to be able to take shortcuts and navigate through detours in familiar environments (Spiers & Maguire, 2008). Factors that affect human navigational performance include the layout of the environment (for example a grid system vs. no discernable pattern), familiarity with the environment, density and /or saliency of landmarks, and the individual differences in spatial processing capacity (Lövdén et al., 2007; Spiers & Maguire, 2008).

1.7 Rationale for Concurrent Aerobic & Executive Challenge Using Navigation

Interventions that have examined the effects of exercise on executive capacity predominately implement aerobic exercise. This exercise, in and of itself, has been shown to promote improvement to executive function (Chang, et al., 2012; Chang et al., 2014). The mechanisms behind these improvements are multifactorial: exercise leads to an increase in the production and release of neurotrophic factors, neurotransmitters and lactate (Cassilhas et al., 2016; Cotman et al, 2007; Magistretti & Allaman, 2018; Voss et al., 2013). These neurotrophic factors serve to further influence plasticity: BNDF and IGF-1 are believed to influence neuroplasticity and neurogenesis while VEGF is believed to promote angiogenesis and the connections between neurons and their associated vasculature (Cassilhas et al., 2016; Cotman et al, 2007; Magistretti & Allaman, 2018; Voss et al., 2013). While exercise has been shown to improve inhibition, memory and attention, there is little support for its improvement to spatial function. Executive training, on the other hand, promotes improvements to executive function, primarily in the domain that was trained. The literature suggests that there is little transfer of training effects to tasks that are quite different from the domain that is trained (Binder et al., 2015; Reijnders et al., 2013). Therefore, if the aim is to improve spatial function, individuals would be trained with a spatial task. Spatial functions are heavily reliant on the hippocampus as this structure supports long term memory and spatial navigation (Wiener et al., 2009; Wolbers & Hegarty, 2010). Of importance is the notion that the hippocampus is highly susceptible to plasticity induced by exercise, spatial-executive training, and environmental enrichment (Kempermann et al., 2010). Recent work by Anderson-Hanley et al. (2012, 2014) and Barcelos et al. (2015) reveal the potential of concurrently coupling aerobic cycling with virtual navigation games or tasks, suggesting that coupling aerobic exercise with a virtual navigation task may not only be feasible, but also have the potential to promote improvements to multiple domains of executive function.

Therefore, if exercise promotes an environment that increases the potential for plastic changes within the brain, in particular the hippocampus, will the addition of a spatial navigation task further augment hippocampal plasticity? This could lead to changes in connectivity between the hippocampus and the prefrontal cortex. If the exercise improves executive function, and the spatial navigation improves spatial function, and these combined factors augment hippocampal plasticity and PFC connectivity, this may lead to improvements to general cognitive function, and activities of daily living.

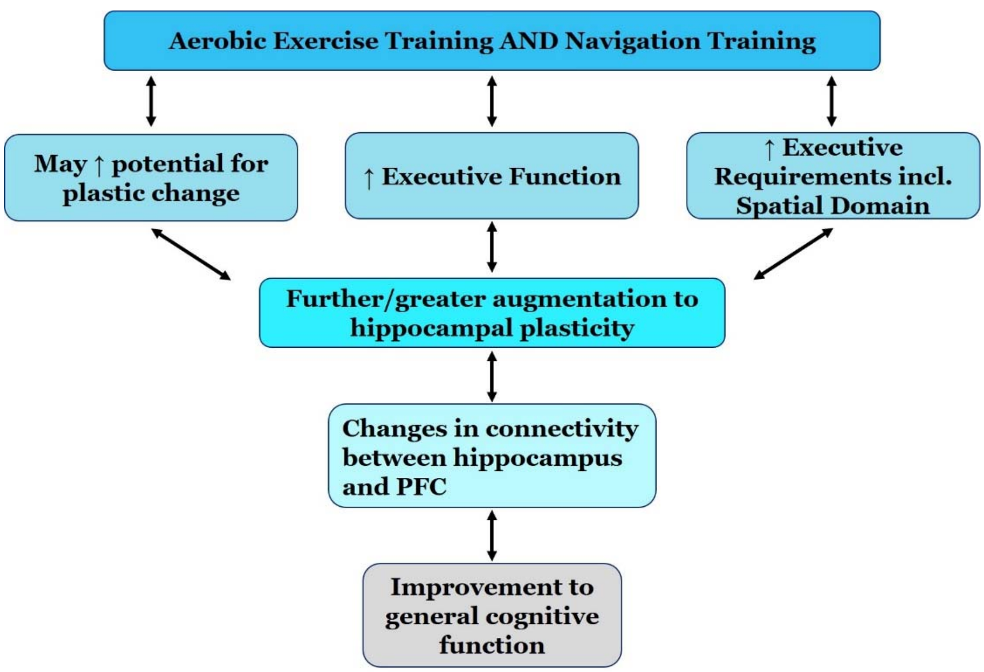


Figure 1.1: Model outlining the potential benefits of concurrently combining virtual navigation with aerobic exercise on executive function, overall cognition and the possible mechanistic underpinnings.

1.8 Challenges for Optimizing the Development and Implementation of a Virtual Navigation & Exercise Program

While evidence exists in support of the concurrent delivery of exercise and executive training for a variety of age groups, they are not without limitations that inform an approach to optimize the potential benefits. Essential to a concurrent coupling paradigm is the fact that individuals will need to perform two tasks: the exercise and the executive task. As previously noted, it is proposed that virtual navigation may provide an effective executive training demand involving multiple executive processes, which in turn may maximize generalizability of training benefits, and is inherently linked to control of mobility. Studies by Anderson-Hanley et al. (2012, 2014), Barcelos et al., (2015), and O'Leary et al. (2011) have revealed the potential feasibility of this concurrent training approach in various age groups. However, what is critical for the evaluation and potential deployment of a concurrent exercise-executive training paradigm is carefully attending to the control of the challenges of *both* the exercise task and the virtual navigation task. Research involving the implementation of exercise for improvements to brain function controls for dosage of exercise prescription; cardiovascular fitness is assessed in some manner, and exercise intensities, durations and frequencies are applied using various adaptations of the FITT Principle (Frequency, Intensity, Time and Type of exercise). As participant fitness and ability improve over time, as measured through VO_2 or heart rate, parameters of the exercise are altered to ensure that the desired exercise intensities are maintained (Wilson et al., 2016). Previous research examining concurrent exercise-executive training have rarely prioritized the assessment of whether or not the addition of a simultaneously performed executive task influences the dose of the exercise. Similarly, it is expected the intensity of the task challenge for virtual navigation is essential for optimizing the benefits to brain function. Control of task challenge (actual and perceived) is not well addressed in the literature. The relative inattention to the control of task challenge is likely to have muted the potential benefits of this approach to maximize health outcomes. When implementing a concurrent exercise-executive challenge, dosing the intensity of both tasks will be essential to the success of evoking adaptive benefits in both brain and body systems. The focus of the current work is to develop and evaluate an approach that would exert careful attention and control over task challenge in order to advance an approach that could eventually be deployed to various populations.

1.8.1 The Issue of Dual-Task Trade-Off

A core challenge of concurrent performance of exercise and executive tasks is that this ultimately creates a dual-task paradigm. A dual-task paradigm requires maintaining, coordinating and integrating information from two separate tasks, in the case of this thesis, the executive demands required to maintain the exercise and the executive demands required of the virtual navigation task (Wong et al., 2015). Dual-task paradigms have shown that both younger and older adults experience performance decrements while performing multiple tasks concurrently, however older adults show greater deficits compared to young adults (Wong et al., 2015). As previously mentioned, the ability to dual-task is necessary for activities of daily living, and this ability decreases with age (Ogawa et al., 2016).

Dual-task training is commonly implemented by having individuals perform a cognitively demanding task while performing a locomotion task (over-ground walking or on a treadmill), in order to improve executive function in an ecologically valid way, as both executive and motor function declines are observed in older adult populations (Hsu et al., 2016; Pedroli et al., 2018). Executive functions are required for the maintenance of postural stability and integration of extrinsic sensorimotor information from the environment in order to promote safe locomotion (Beauchet et al., 2012; Liu-Ambrose et al., 2009; Nagamatsu et al., 2011). Nagamatsu et al. (2011) examined the ability of older adults to perform a cognitive dual-task paradigm, as well as their ability to perform an ecological dual-task paradigm of crossing a virtual street while conversing on a phone. This cohort was divided into those who were considered to be at risk for experiencing a fall and those who were not. The fall risk group performed worse on the cognitive dual-task paradigm compared to their non-faller counterparts, and also performed worse on the cognitive-motor dual-task paradigm, as evidenced by their reduced gait speed and metrics of street crossing success (Nagamatsu et al., 2011).

A gap in the literature is that studies implementing concurrent aerobic and executive training do not characterize the behavioural components or outcomes of the exercise itself, or address the possibility of dual-task trade-offs. Are individuals making sacrifices to the performance of the exercise in order to maintain the performance of the executive task? Are individuals able to maintain their heart rate within a targeted aerobic heart rate zone while performing this dual-task paradigm? Are participants able to achieve *both* aerobic and executive benefits of a concurrent exercise-executive training program? While results so far show the potential for executive benefits, it is unclear as to the potential of achieving an aerobic benefit. If aerobic benefits are not attained, then it may speak to the need to perform some aerobic exercise without an additional executive demand, in addition to the concurrent training paradigm, in order to achieve other cardiovascular and musculoskeletal health benefits of cardiovascular exercise.

1.9 Thesis Rationale & Objectives

The overarching objective of this thesis was to develop and evaluate a concurrent exercise-executive training paradigm, specifically by implementing a task that coupled aerobic cycling with virtual navigation. This work addressed methodological considerations linked to approaches to understanding and controlling task challenge and dual-task trade-off effects that occur when concurrently coupling an aerobic challenge with executive tasks. Specifically, this work begins to address the concern of not only considering how to dose the exercise for the individual, but also considerations that may be important for dosing the executive task demand.

1.9.1 Research Objectives

This thesis is characterized by four studies, which address the following research objectives:

Study 1: Feasibility of Coupling Aerobic Exercise with Executive Tasks:

- To determine if young healthy adults can maintain a prescribed aerobic cycling workload, as measured by workload and heart rate, during the concurrent performance of executive tasks?

Study 2: Individual and Task Factors that May Influence Virtual Navigation Performance:

- The objective of this study was to examine task related factors and individual related factors that may influence the task challenge during virtual navigation performance in young healthy adults.

Study 3: Specific Dual-Task Trade-Offs of Aerobic Cycling Coupled with Virtual Navigation:

- The primary objective of this study was to examine the specific dual-task trade-off effects of concurrently combining aerobic cycling with virtual navigation

Study 4: Changes in Dual-Task Effects over Repeated Exposure

- The primary objective was to explore the changes in dual-task trade-off, as measured by changes in physical exercise performance and/or cognitive task performance, over repeated exposure to the training regime

- The second objective was to determine in if perceptions of fatigue and mental effort would be reduced following repeat practice of dual task performance

Potential Impact for Future Research:

The objectives of this thesis are to lay foundational work necessary for considerations with regards to appropriately dosing both the exercise and executive challenges for older adult participants, clients, and patients.

Chapter 2: Study 1

The Feasibility of Concurrently Coupling Aerobic Cycling with Executive Tasks in Young Healthy Adults

2.1 Introduction

The prevalence of age related disease and degeneration is expected to increase drastically over the next decade in conjunction with the aging population (Bherer, 2015). A major area of concern is the decline in executive function that is associated with the aging population, through means of "normal" age related executive decline, dementia, Alzheimer's Disease and executive deficits incurred as a result of stroke (as this population is at a greater risk for stroke) (Erickson et al., 2013). These executive deficits include decrements in memory, attention, dual-tasking ability, speed of processing, and inhibition (Shatil, 2013). Therefore, there has been an abundance of research regarding ways in which these decrements in executive capacity may be muted, or potentially even reversed. An emerging area of study is the focus of participation in a regular exercise program and the potential benefits to executive function.

Exercise has been shown to be a means of improving executive performance throughout the lifespan. Children who are physically active tend to demonstrate higher academic performance compared to their non-active counterparts (Hillman et al., 2012; Phillips, 2017). Staving off executive decline and potentially even improving executive function in older age groups, including those with executive impairments, is a beneficial effect of exercise at the other end of the age spectrum (Cassilhas et al., 2015; Colcombe et al., 2004; Erickson et al., 2013 & Hötting & Röder, 2013).

Some of the benefits to executive function associated with exercise appear to be linked to improvements in cerebrovascular function as well as increased levels of neural growth factors such as brain derived neurotrophic factor (BDNF) and insulin-like growth factor 1 (IGF-1) (Chang et al., 2012). Many studies have examined changes to brain function after a single bout of exercise. These studies have the prevailing finding that cortical activity is enhanced for approximately 30 minutes after the completion of a 20-30 minute bout of moderate intensity aerobic exercise (Chang, et al., 2012). These single bouts have shown improvements in executive function as demonstrated by decreased response times in both simple and choice reaction time tasks, as well as shorter P3 latency in tasks that required greater amounts of executive function (Hillman et al., 2003; Kamijo et al., 2007). Evidence from chronic exercise participation has shown improvements to executive function as well as structural changes to the brain. Erikson et al., (2011) found that older adults who participated in a 6 month walking program had an increase in anterior hippocampal volume. These participants also improved their performance on a spatial-memory task over the course of the study (Erickson et al, 2011). Colcombe et al., (2004) examined a cross-sectional study in conjunction with a 6 month exercise intervention on separate groups of community dwelling older adults. The results indicated that adults with better cardiovascular fitness performed better on the Flanker task; and those who underwent the 6 month walking regime improved their performance on the Flanker task compared to their pre-exercise performance (Colcombe et al., 2004).

While exercise alone is beneficial to executive function and underlying brain health, there is evidence that executive training alone has significant benefits to executive function. Such interventions have demonstrated improvements across multiple domains, including:

inhibition, processing speed, and working memory (Hötting, et al., 2013). Shatil et al. (2014) examined executive abilities in older adults who used an interactive television system to train executive function. After an 8 week intervention period, they found that participants in the executive training group showed improvement in the Trails A & Trails B tasks, as well as the forward and reverse Digit Span tasks compared to those in the control group (Shatil et al., 2014). A review by Belleville & Bherer (2012) examined structural and functional changes within the brain in response to executive training. Their findings suggest that at the structural level, executive training can induce changes in brain volume, white matter integrity and increase cortical thickness. At the functional level, resting and task-related brain activity were altered, such that individuals with mild cognitive impairment (MCI) showed increased cortical activity while performing cognitive tasks (Belleville & Bherer, 2012).

Of specific interest in the present study is a focus on visuospatial function. Visuospatial skills engage a broad network of cortical regions important for executive function, and these areas are susceptible to neuroplastic change. Human spatial navigation is predominately sub-served by the hippocampus which houses highly specialized neurons responsive to movement through the environment (Moser et al., 2015). The hippocampus shares connections to the prefrontal cortex to enable flexible navigational behaviour in order to achieve a desired goal, creating natural links to rhythmic, locomotor activity, and thus are critical for our ability to perform activities of daily living (Moffat, 2009; Spires & Gilbert, 2015). Additionally, our visuospatial abilities decline with age, neurodegenerative disorders and stroke. There is ample research demonstrating that spatial abilities in rodents improve with executive and/or spatial training and that these animals generally demonstrate increased hippocampal volume post intervention (Hötting et al., 2013). Spatial training not only leads to improvements in human performance on navigation tasks, but it has also been shown to stave off hippocampal volume loss associated with aging (Hötting et al., 2013; Lövdén et al., 2012).

If aerobic exercise training and executive training in isolation have benefits to executive function, it raises the possibility that combining them to be performed concurrently may have the potential to lead to a greater improvement in executive function. Grealy et al. (1999) argued that enriched environments that enabled traumatic brain injury (TBI) patients to interact with the environment would lead to both behavioural and physiological improvements in brain function. They examined the concurrent coupling of aerobic exercise and virtual environments to increase the interaction of TBI patients within an environment and found that individuals improved their learning ability in visual and auditory tasks, but did not show improvements in memory tasks (Grealy et al., 1999). They also noted that there was an increase in exercise adherence when the cycling exercise was coupled with the virtual environment. While there is the promise of positive benefits from the concurrent application of exercise and executive training, there is also the potential problem of dual-task trade-offs between maintaining the aerobic challenge of the exercise as well as maintaining performance of the executive task. A common challenge in in gait studies is that individuals will slow down or even stop moving entirely when asked to simultaneously perform an executive task (Nadkarni, et al., 2010; Nagamatsu et al., 2011). Such dual-task effects are seen in many conditions, since the two tasks (in this case, the exercise task and the executive task) are independently demanding of shared resources (Abernethy, 1988; Nadkarni et al., 2010;

Nagamatsu et al., 2011). As a result, the primary focus of the current work is to establish the feasibility of concurrently combining executive training with aerobic exercise as a precursor to application for future clinical work.

It was proposed that a navigation task may be an ideal task to use during concurrent training to exploit the natural links between executive function and mobility / exercise as it links movement control via direction, speed, and obstacle avoidance, thus providing a highly ecologically valid dual-task. For humans, navigation is a necessary executive function as it enables us to move and interact in new and complex environments (Wolbers & Hegarty, 2010). Navigation demands numerous aspects of executive function, including working memory, visuospatial working memory, attention, planning and decision making (Bates & Wolbers, 2014; Spiers & Maguire, 2008). Therefore, this provides the opportunity to develop a novel approach to challenge individuals both physically (via workload) and executively (controlled challenge to navigation engaging attention, working memory, planning and decision making) in order to maximize the physical and executive benefits of exercise.

The overall objective of this work was to develop and test the feasibility of concurrently combining exercise with an executive task and examine the dual-task effect of the concurrent performance of both tasks. Feasibility in this case is defined as being able to couple the technology of the exercise equipment and of the executive tasks in a cost effective manner so that both tasks can be performed concurrently. The first stage was to develop a novel approach to combine exercise with visuospatial navigation in an accessible manner (i.e. clinical and home use). This was accomplished by using a recumbent cycle ergometer and a computer with internet access in order to perform a computer based executive task and use Google Earth, a free internet virtual reality (VR) platform that enables the user to navigate through various urban environments.

The second stage was to determine if a dual-task effect occurs, and what task (the exercise or the executive task) shows the decrement in performance. The concern was that the addition of an executive task would decrease the participants' ability to effectively perform physical training, thus reducing or mitigating the aerobic benefits incurred from performing the physical exercise. Potential accommodations of performing the executive task during the exercise was assessed by examining the behaviour changes in cycling cadence and the physiological changes to heart rate in order to assess dual-task cost. Additionally, how do different task challenges, related to either the exercise or the executive task, affect the outcome measures? Different executive tasks have different executive requirements, and that may affect the exercise differentially. Therefore executive task demands were varied to have different levels of difficulty: no additional executive task, a visual search task, an exploration task in Google Earth and a navigation task in Google Earth. Based on work by Beyer et al., (2017), it was hypothesized that cadence would increase and become less variable when participants performed a visual search task as compared to cycling alone. It was further hypothesized that individuals would decrease their cadence and become more variable when performing the navigation tasks in Google Earth.

The potential executive demands of exercise could emerge from the control of workload. Therefore, control of workload was varied by using a constant resistance versus a constant power setting. Under constant resistance, the cycle ergometer is set to a given resistance, and the participant's overall power output varies as a function of their cadence.

Under constant power, the cycle ergometer automatically adjusts the resistance of the bike based on the participant's cadence in order to maintain the desired power output. It is possible constant resistance requires greater executive control in order to maintain the given workload in the face of a concurrent executive challenge. Challenges in maintaining a given exercise level can be monitored through actual and perceived exertion as measured through heart rate and the participant's rate of perceived exertion (RPE) respectively. Again, these provide measures of physiological and psychological differences in exertion during exercise coupled with virtual navigation, based on different task challenges.

It was hypothesized that in young, healthy adults there would be no dual-task trade-off seen in the performance of the exercise (e.g. no change in cadence between constant resistance and constant power) within a given executive task condition. It was further hypothesized that while heart rate would remain unchanged between constant resistance and constant power within a given executive task condition, that heart rate would increase along with the hypothesized increase in cadence during the visual search task, and would decrease along with the hypothesized decrease in cadence during the Google Earth navigation tasks.

2.2 Methods

Participants

Twelve healthy young adults (6 females, 6 males) participated in the study (aged 18-34, mean (sd) age = 25.9 (5.3) years, height = 172.6 (7.2) cm, and weight = 70.6 (12.3) kg. All participants completed the PAR-Q, provided self-reports of their current activity level and activities of interest, and reported no neurological or musculoskeletal conditions that would affect their ability to perform the exercise protocol required for the experiment.

Participants also had normal or corrected to normal vision in order to perform the visual search and Google Earth navigation tasks. This study received clearance from the Office of Research Ethics at the University of Waterloo and all participants provided written consent prior to study participation.

Participant Demographic Information

Category	Female	Male	Cohort Combined
Age (years)	25.3 ± 5.7	26.5 ± 5.2	25.9 ± 5.2
Height (cm)	167.2 ± 5.3	178 ± 3.9	172.6 ± 7.2
Weight (kg)	61.8 ± 9.5	79.4 ± 7.5	70.6 ± 12.3
Preferred Cadence (RPM)	60.8 ± 9.5 (53 – 73)	63.5 ± 11.1 (50 – 82)	62.2 ± 9.9 (50 – 82)
Target Heart Rate (bpm)	126.5 ± 3.6	125.8 ± 3.8	126.2 ± 3.4
Actual Heart Rate (bpm)	130 ± 17	132.4 ± 14.7	131.5 ± 12.7
Actual Work Rate (Watts)	97.7 ± 18.1 (73 – 115)	141.5 ± 16.7	119.6 ± 28.3

Table 2.1: Participant demographic information by sex and as a combined cohort. Values are means ± standard deviation. Values that are in brackets are the range of values within the category.

Overview of General Experimental Set-Up

Participants were seated on a recumbent bicycle (Technogym® 700, Technogym, USA Corp.) that had custom built arm rests mounted on either side of the participant (see Figure 2.1). The bike was placed in front of a projector screen so that the participant was seated 2 meters away from the screen. Participants were connected to a three lead electrocardiogram (ECG) in order to monitor heart rate in real time as well as to measure any differences in heart rate related to the different executive tasks performed while cycling. Participants additionally wore an eye tracker in order to determine the trial lengths of the visual search task.

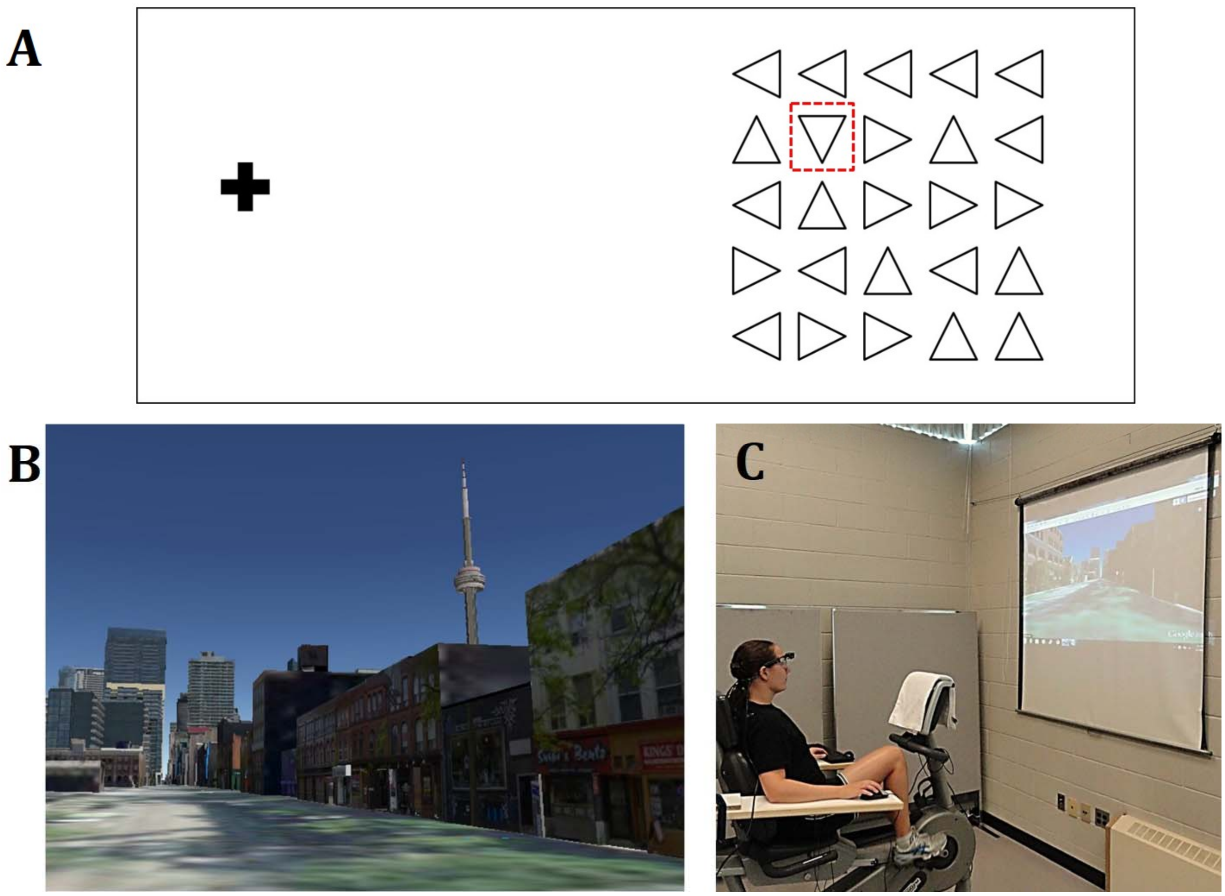


Figure 2.1: Experimental methodology for study 1. **A**) The Visual Search Task: the plus (+) sign on the left served as a fixation point that would disappear when the matrix of triangles appeared. The downward triangle (highlighted) was the target triangle participants were to visually locate; **B**) Rendered version of Google Earth street view in the city of Toronto; **C**) Experimental set-up within the laboratory setting.

Task Conditions:

1) *Single Task: Exercise*

In this case, the only task that the participant was required to perform to cycle (CYCLE). No other additional executive task demands were placed on the participant.

2) *Single Task: Executive*

In order to increase executive load, participants performed a visual search task (VST). In this task, a fixation cross was presented on the left hand side of the screen for a randomized time period between 500 – 2000 msec. When the fixation cross disappeared, there was a 1 second delay followed by the appearance of a 5x5 matrix of triangles on the right hand side of the screen (see Figure 2.1 A). The triangles were presented in various orientations, with only one triangle pointing in the downward direction. This was the target triangle that participants were asked to locate by performing a visual search with their eyes. Once they had located the target triangle, participants performed a left mouse click with their right hand which caused the 5x5 matrix of triangles disappear and the fixation cross to reappear in order to start the next trial. This process continued for the entirety of the task block which was 4 minutes in length.

3) *Dual-Tasks: Exercise & Executive Concurrently Combined*

The navigation tasks used to increase executive demand on the participant were implemented in a virtual environment provided my Google Earth in the 3D rendered version of street view. Movements through the environment were performed using a keyboard to make turns (left and right using the left and right arrow keys of a computer keyboard). The forward propulsion of the individual through the Google Earth environment was achieved as a result of their pedaling motion from a sensor mounted on the bike frame and on the pedal. All blocks were 4 minutes in length.

a. Navigation

In the navigation task (NAV), participants were given a start point (a specific building) in Toronto or Mexico City, and were asked to find their way from the start point, to a target point of interest in the distance (a tall tower or building), and then back to the start point.

b. Explore

In the other navigation condition, participants were once again immersed in Google Earth, but were given no specific instruction, other than to avoid going through buildings. They were asked to freely explore the VR environment of the city of Calgary or Tokyo. This was referred to as the explore (EXP) condition.

c. Visual Search Task

The visual search task (VST), described above was later coupled with the aerobic cycling task in order to increase the executive load of the dual-task paradigm when cycling.

4) Familiarization Session

This session was used to familiarize participants with the executive tasks that would be performed in the experimental protocol as well as to determine the bike settings that would be required to elicit their target heart rate. During this session, participants were given a 1 minute practice trial for the VST prior to performing three 4 minute blocks of the VST, with a 3 minute break in between blocks. Participants were then asked to begin cycling, and the resistance on the bike was increased until their target heart rate, 65% of their age predicted maximum heart rate, was reached. Once target heart rate was reached, participants again performed one 4 minute block of the VST. Once this was complete, participants were familiarized with the visual scene and controls used to navigate through Google Earth. A keyboard was provided to participants and was mounted on the left armrest of the custom frame of the cycle ergometer. Participants used the arrow keys on the keyboard to move through the Google Earth environment. The preferred cadence while cycling and performing the VST, along with the resistance level of the bike which corresponded to the desired heart rate were used to calculate the power output that would be used for the constant power exercise session. The preferred cadence while performing the VST task was used in the warm up phase for both experimental sessions, and then visual feedback of cadence was removed. This was done as a means to offset the chance of falsely interpreting an increase in cadence from cycling alone to cycling while performing the VST.

5) Experimental Dual-Task Session: Exercise & Executive Tasks

Participants performed two 4 minute blocks of the VST task prior to the initiation of exercise. Once those blocks were completed, they began a warm up period on the bike in order to reach their target heart rate (approximately 5 minutes). Once target heart rate was reached, there were six 4 minute blocks of tasks performed by the participants, for a total of approximately 30 minutes of exercise, including the warm up. Blocks 1 & 2 were block randomized between the CYCLE and VST, blocks 3 & 4 were block randomized between EXP and NAV tasks, and blocks 5 & 6 were block randomized between CYCLE and VST tasks (see Figure 2.2). The VST was performed again immediately after exercise, and again 15 minutes after the completion of the previous VST after heart rate had decreased.

6) Experimental Dual-Task Session: Effect of Bike Settings

In order to examine the influence of the settings of the exercise equipment to cycling cadence and heart rate, two experimental sessions were used. In the constant resistance (CON RES) setting, the stationary bike was set to a constant resistance level such that the power output in watts would vary over the course of the exercise session as a function of any variation in cadence. This workload set up is common of most exercise equipment. In the constant power (CON PWR) setting the stationary bike adjusted the resistance based on the participants' cadence to ensure that the required power output was maintained. This setting is not available on all exercise equipment. However, if the constant power setting showed that participants were better able to maintain their heart rate, it may speak to the need to have equipment with such capabilities. The two dual-task exercise sessions were carried out in a block randomized order between the constant power and constant resistance sessions.

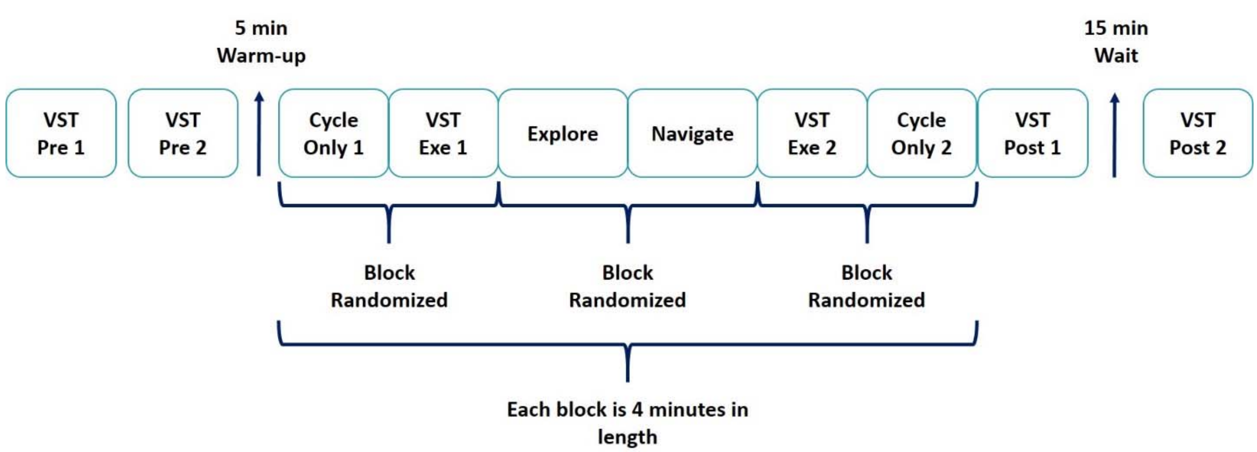


Figure 2.2: Protocol for the implementation of cognitive tasks that were concurrently combined with aerobic cycling. This implementation strategy was used for both the constant resistance and constant power sessions.

2.3 Instrumentation & Data Acquisition

Electrocardiography was collected from each participant with self-adhesive electrodes from three electrode sites. The first electrode was placed on the superior portion of the sternum (manubrium), and the second and third electrodes were placed on either side of the ribs just below the bottom of the bra for women and just below and lateral to the outside of the nipple line for men. Skin sites were first abraded with NuPrep skin preparation gel and then cleaned with rubbing alcohol. Participants were also asked to report their rate of perceived exertion (RPE) on the 10 point Borg scale (Appendix A) at the end of each 4 minute block.

Participants wore a head mounted eye tracker (Eye Tracker 5000, ASL, Bedford MA, USA) in order to record eye movements. The eye tracker was calibrated by having participants fixate at different computer icons. For this, the computer background was projected onto the screen that participants used to perform the VST and the navigation tasks. An icon was placed in each corner of the screen and then others were placed randomly throughout the remaining screen area. Each of these fixations produces a vector between the reflection of the pupil and the cornea which is distinct for each fixation, providing a distinct line of gaze (Miyasike DaSilva et al., 2011). The eye tracker collection system superimposes a gaze cursor representing the individuals' line of gaze overtop of the visual scene of the environment which is captured by a head mounted scene camera. The eye tracker data enabled the determination of the number of trials performed and the length of each trial for each 4 minute VST block.

2.4 Data Analysis

Data were analyzed using a custom built LabView program (National Instruments, Austin TX, USA). Revolutions per minute were recorded by a cycle pulse box that was embedded next to the fly wheel of the stationary bike. Every revolution of the fly wheel was recorded by the computer, and a peak detection program calculated cycle to cycle intervals, after which the reciprocal was taken to calculate cadence mean and variability. Cadence variability was calculated as the average standard deviation of cycling cadence in RPM across the individuals. Power output was determined over the course of each block from the revolutions per minute (RPM) samples and the resistance level that the bike was set to for the individual. Heart rate data was run through a dual-pass, bandpass, second order Butterworth filter, with low and high frequency cut-offs of 500 and 1 Hz, respectively. Heart rate values were calculated as beat to beat intervals, and the reciprocal was then taken in order to calculate heart rate and heart rate variability within each 4 minute block. This provided a physiological measure of perceived exertion of the participant.

The eye tracker file was initially processed with a custom built LabView program in order to determine the fixations that occurred over the block. This was then manually compared to the video recorded with the eye tracker scene camera in the video processing program VirtualDub (free video software download by Avery Lee; available from http://www.virtualdub.org/).

2.5 Statistical Analysis

A one-way repeated measures ANOVA was performed on the RPM mean and RPM variability data from the constant resistance setting. This was done initially to examine for a possible effect of block vs. task between the CYCLE 1 and CYCLE 2 blocks, as well as the

VST-EXE 1 and VST-EXE 2 blocks (VST-EXE blocks are when the visual search task was performed while exercising). No difference was found between the blocks within each respective executive task condition, and therefore the values were averaged over the two blocks within each condition. The collapsed data was also used to analyze differences in power output, as the original repeated measures ANOVA also showed no effect of block with respect to power output. The original data set was used to analyze heart rate, as there was an effect of block. The findings are presented with respect to the constant resistance setting, as this is the setting that is most common on commercially available exercise equipment. Subsequently, the analysis of visual search task performance is also shown with respect to the constant resistance setting. A two-way repeated measures ANOVA was performed with the bike setting (constant power vs. constant resistance) and task (CYCLE 1, VST-EXE 1, NAV, EXP, VST-EXE 2 and CYCLE 2) as factors within the ANOVA. Post hoc testing was performed with a Tukey's test, and for the visual search task was performed using the Tukey-Kramer test to adjust for multiple comparisons. Significance level was set to $\alpha = 0.05$.

2.6 Results

Mean Pedalling Cadence by Task

In the constant resistance setting, mean (± sd) cadence for the cycle only task was 63.3 ± 10.4 RPM, for the visual search task was 64 ± 11.5 RPM, for the navigation task was 60.6 ± 11.7 RPM and for the explore task was 60.3 ± 11.7 RPM (Figure 2.3 A). There was no significant difference in mean RPM between any of the four separate tasks ($F_{3,47} = 4.06$ ($p = 0.140$)).

Pedalling Variability by Task

In the constant resistance setting, the average standard deviation in cadence for the cycle only task was 2.07 RPM, for the visual search task was 1.43 RPM, for the navigation task was 2.67 RPM and for the explore task was 2.47 RPM (Figure 2.3 B). The main effect of task condition approached significance, ($F_{3,47} = 5.18$ ($p = 0.0559$)) indicating that variability in pedalling changed depending on executive task condition. Post hoc results revealed that cadence variability was greater in the navigation task ($p = 0.014$) and the explore task ($p = 0.023$) when compared to the visual search task. Cycling alone was not statistically significantly different when compared to the visual search task, the navigation task or the explore task ($p > 0.05$).

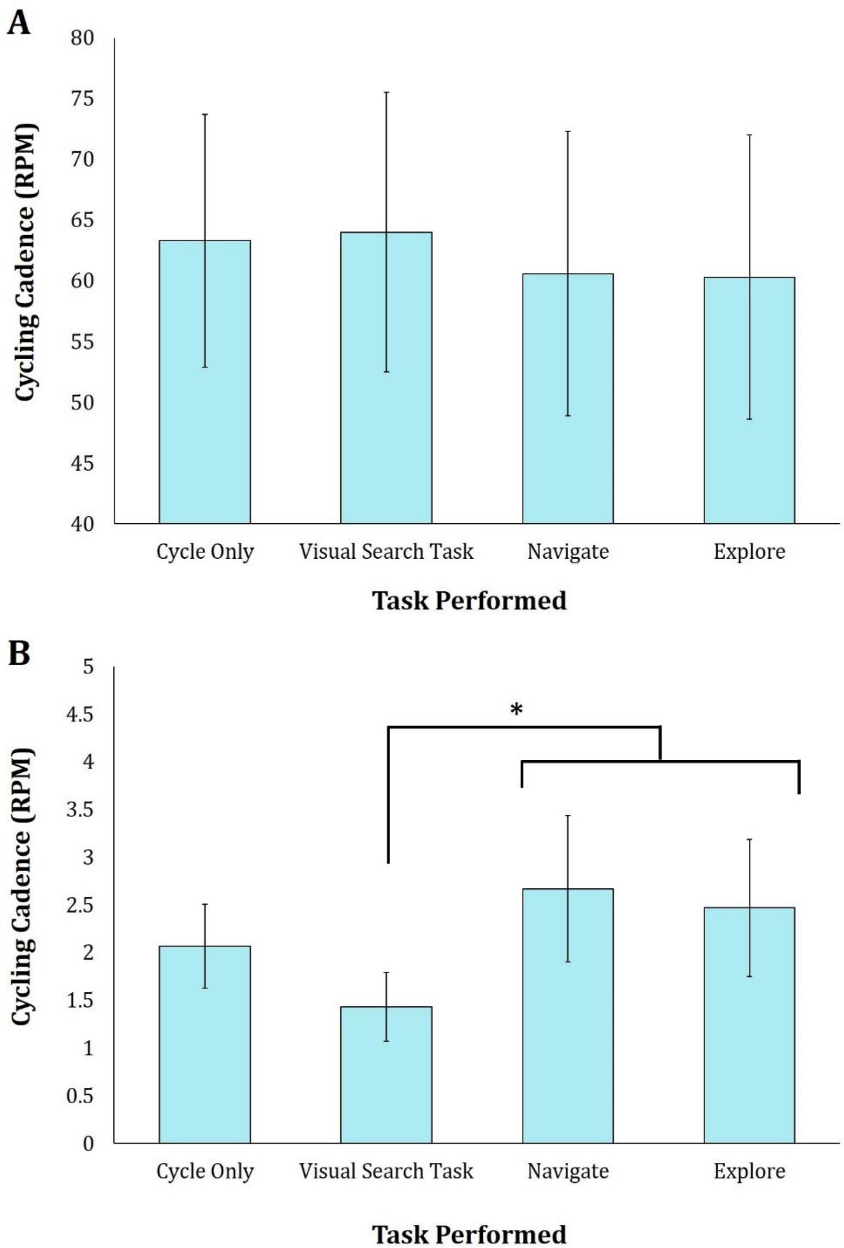


Figure 2.3: A) Mean (± sd) cycling cadence during the four tasks paired with aerobic cycling: cycling only (no secondary task), visual search task, navigation task and the explore task.
B) Mean cycling cadence variability for the different tasks that were paired with aerobic cycling. This data is for the constant resistance session. * $p < 0.05$

Power Output by Task

In the constant resistance setting, the average power output in Watts (W) for the cycle only task was 122.3 ± 32.2 W, for the visual search task was 123.7 ± 33.6 W, for the navigation task was 117.6 ± 34.3 W and for the explore task was 116.9 ± 33.8 W (Figure 2.4). There was no main effect of average power output (W) between the task conditions of cycle only, visual search task, navigation and explore ($F_{3,47}$ = 4.51 (p = 0.124)).

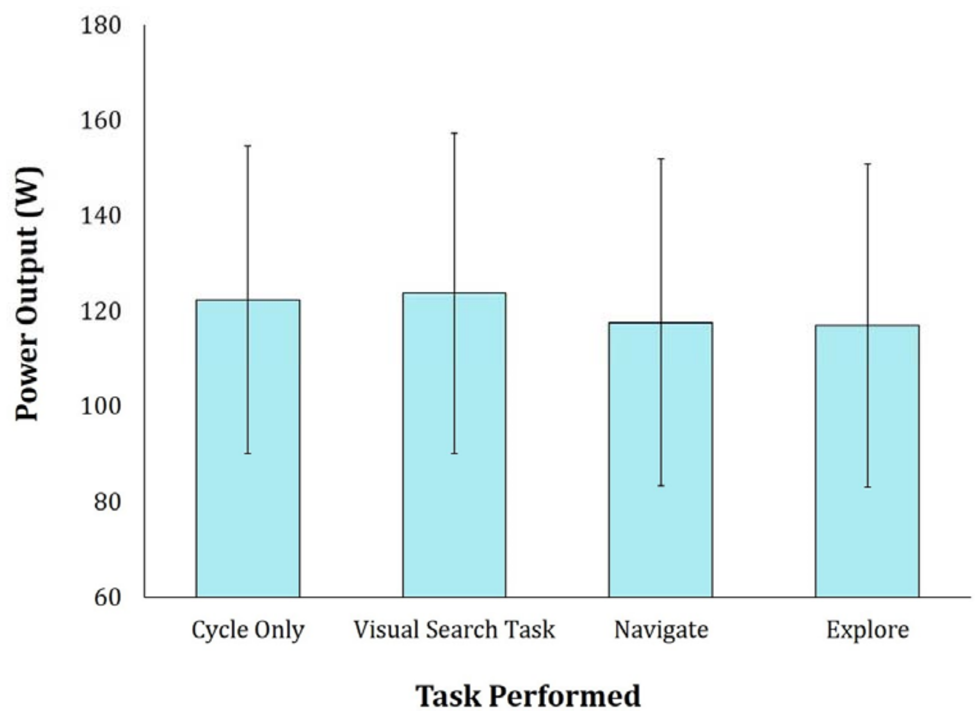


Figure 2.4: Mean (± sd) power output in Watts during the four different tasks that were paired with the aerobic cycling: cycling only (no other secondary task), visual search task, navigation task and the explore task. This data is from the constant resistance session.

Rating of Perceived Exertion by Task

A one-way repeated measures ANOVA demonstrated that there were differences in RPE across time, and therefore this comparison was not collapsed by block ($F_{5,71} = 6.87$ ($p = 0.027$)). The average RPE values were as follows: 3.6 ± 1.5 for CYCLE 1, 3.5 ± 1.2 for VST EXE 1, 4.1 ± 1.7 for NAV, 3.9 ± 1.7 for EXP, 4.4 ± 2 for VST EXE 2, and 4.3 ± 2.1 for CYCLE 2. Post hoc testing revealing that the RPE for CYCLE 2 was statistically significantly higher than for CYCLE 1 ($p = 0.008$). The RPE for VST EXE 1 was significantly lower than the navigation task ($p = 0.011$), VST EXE 2 ($p = 0.002$) and CYCLE 2 ($p = 0.003$) and approached significance as being significantly lower than the RPE for the explore task ($p = 0.057$). The RPE for CYCLE 1 was not statistically different from VST EXE 1 ($p = 0.609$) or from the explore task ($p = 0.285$) but was statistically significantly lower than the RPE reported during the navigation, VST EXE 2 and CYCLE 2 tasks ($p < 0.04$).

Heart Rate by Task

A one-way repeated measures ANOVA demonstrated that there were no statistically significant differences in heart rate across task ($F_{5,60} = 1.36$($p =0.37$)). The average heart rate for CYCLE 1 was 128.8 ± 11.9 beats per min (bpm) and for CYCLE 2 was 135.1 ± 14.5 bpm. The average heart rate for VST-EXE 1 was 129.9 ± 10.9 bpm and for VST-EXE 2 was 136.4 ± 14.7 bpm. The average heart rate for navigation and explore were 131.6 ± 13.4 BPM and 127.7 ± 14.4 bpm respectively. This can be seen below in Figure 2.5

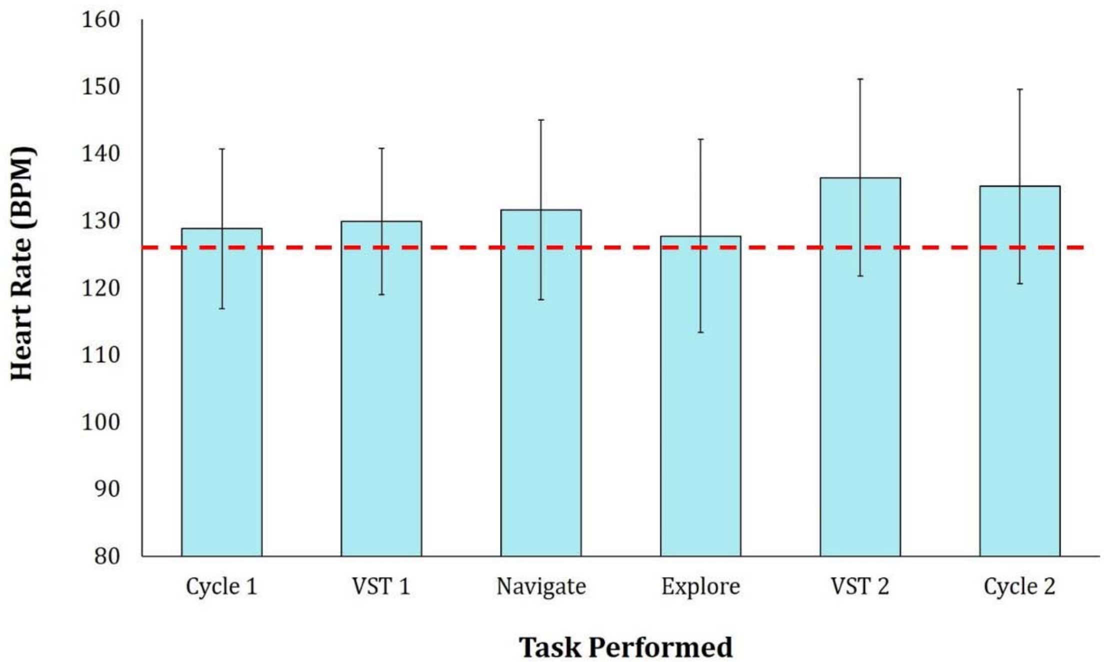


Figure 2.5: Mean (± sd) heart rate in beats per minute across the exercise bout during the six different block sessions that occurred in the constant resistance session. The red dashed line represents the average target heart rate of the group of participants.

Visual Search Task Performance

Participants improved their performance on the visual search task over blocks. The data from the familiarization session and the constant resistance session can be seen in Figure 2.6. The average trial length in the familiarization session demonstrated a significant improvement from trial 1 through trial 4 (VST with exercise) ($F_{9,7307} = 65.99$ ($p < 0.001$)).

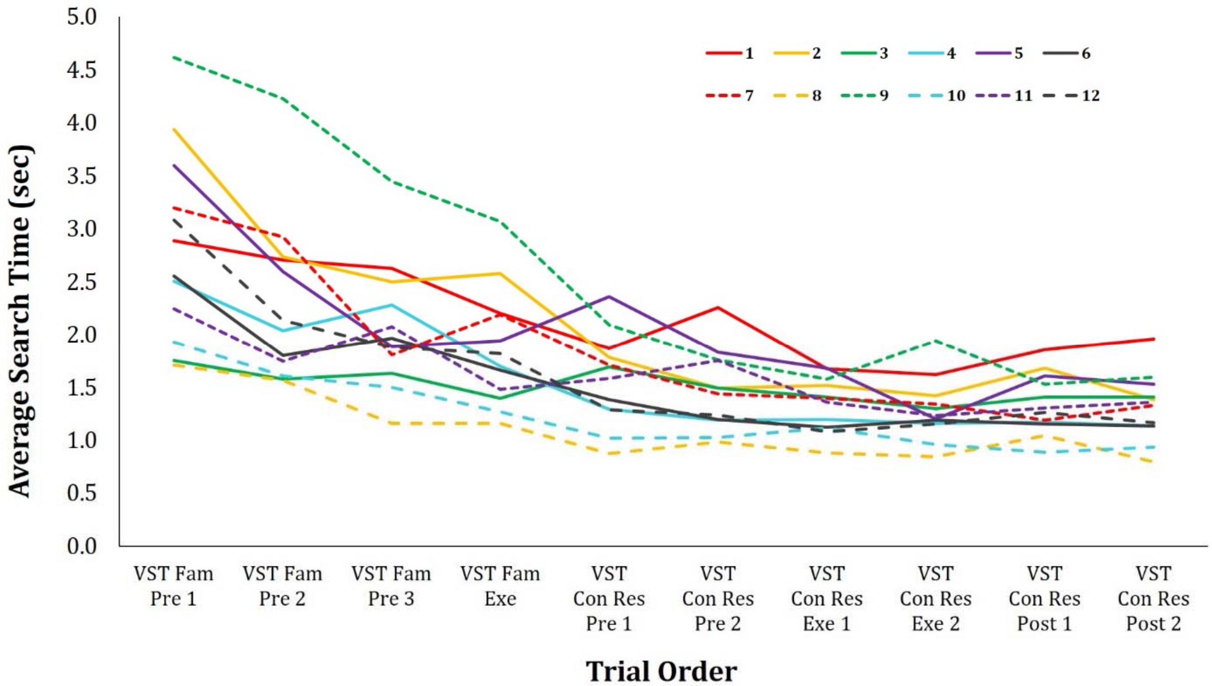


Figure 2.6: Individual performance in the visual search task. The first four points are from the intake / familiarization session, while the following six points are the performance blocks during the constant resistance sessions.

Constant Resistance vs. Constant Power

For mean RPM there was no main effect of bike setting ($F_{1,5} = 38.01$ ($p = 0.102$)), indicating that participants did not adopt different average cycling cadences between the constant resistance (mean = 62.6 RPM) and constant power (mean = 65.7 RPM) settings. There was also no main effect of task ($F_{1,5} = 2.84$ ($p = 0.134$)) and no interaction effect between bike and task ($F_{1,5} = 2.36$ ($p = 0.184$)).

When examining RPM variability, measured as average standard deviation, there was no main effect of task ($F_{1,5} = 2.27$ ($p = 0.194$)), and no interaction effect ($F_{1,5} = 0.62$ ($p = 0.696$). However, the main effect for bike setting approached significance ($F_{1,5} = 107.54$ ($p = 0.061$). Cadence variability in the constant power setting was 2.67 RPM while cadence variability in the constant resistance setting was 2.02 RPM when averaged across all tasks.

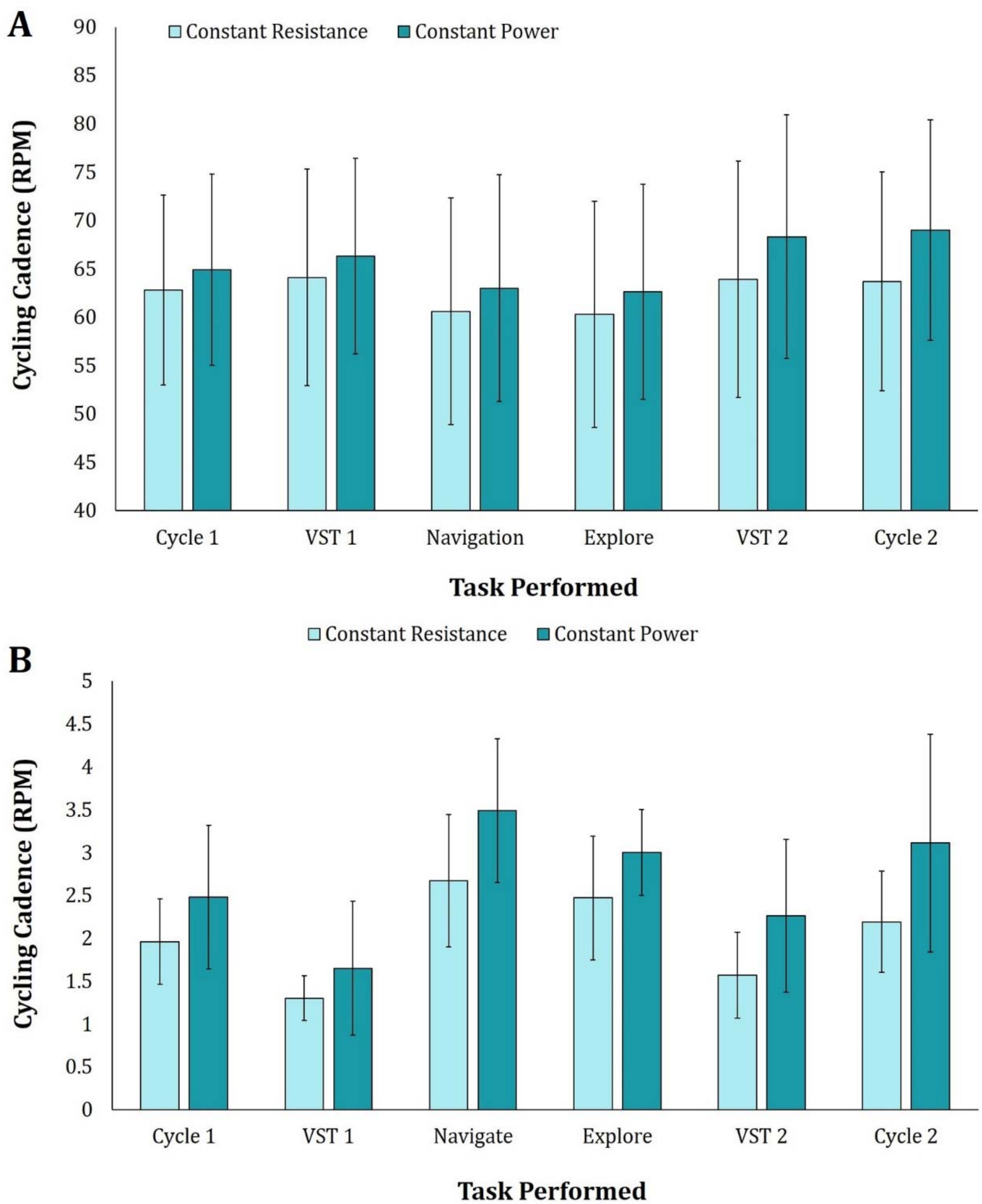


Figure 2.7: A) Mean (± sd) cycling cadence across the exercise bout during both the constant resistance and constant power bike settings. **B**) Mean cycling cadence variability (± sd) across the exercise bout during both the constant resistance and constant power bike settings.

With respect to heart rate, there was no main effect of task ($F_{1,5} = 1.10$ ($p < 0.459$)), no main effect of bike setting ($F_{1,5} = 0.98$ ($p = 0.504$)) and no interaction effect ($F_{1,5} = 1.23$ ($p = 0.411$)), indicating that heart rate was not different between the two bike settings as was anticipated.

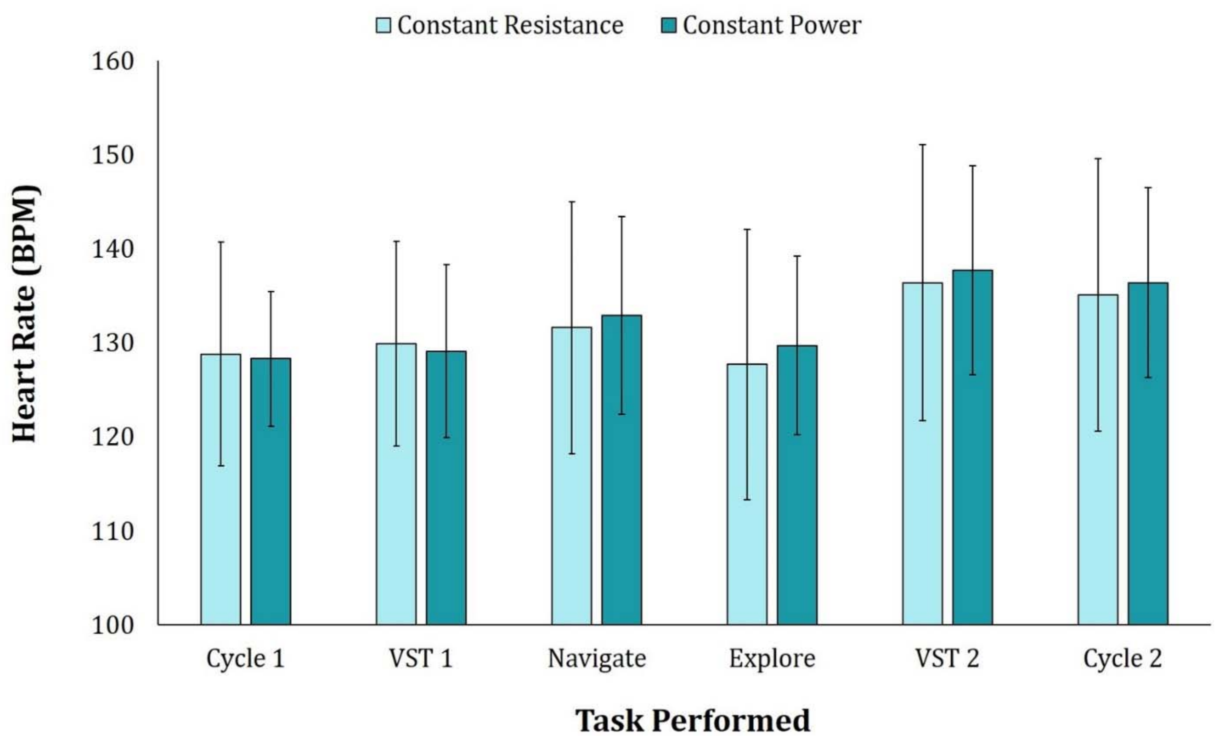


Figure 2.8: Mean (± sd) power output in Watts across the exercise bout during both the constant resistance and constant power bike settings.

2.7 Discussion

The overall objective of this work was to develop and test the feasibility of concurrently coupling aerobic exercise with executive tasks and examine the dual-task effects to the performance of the exercise. This study focused on an accessible way to couple aerobic cycling with secondary executive tasks by using a computer projected image and a computer mouse and keyboard to enable interaction with the executive tasks in a concurrent manner.

The hypothesis regarding changes to the mean cadence (RPM) was not supported. It was hypothesized that there would be a difference in mean cadence between the cycling only condition and the cadence when performing the visual search task, however these were not significantly different. It was also hypothesized that the mean cadence during the navigation and explore tasks in Google Earth would lead to a decrement in mean cadence when compared to cycling alone, and this was also not supported. The hypothesis regarding changes to cadence variability as measured by the average standard deviation of RPM over the task block was partially supported. Cadence variability decreased in the visual search task compared to the two Google Earth tasks of navigation and explore, but the variability in cadence was not different between the cycling only task and the navigation or explore tasks.

As expected, the performance of the visual search task did show a short term adaptation effect with improvement over time. Of importance, the performance of the visual search task during the exercise of the constant resistance session (and the constant power session, not shown) was not different from the post exercise blocks within each respective session, indicating that participants were not sacrificing the performance of the visual search task in order to maintain their exercise intensity.

The ability to adapt cadence during exercise is important, as it enables the individual to optimize the physiological demands of the exercise (oxygen use and muscle metabolism) and the desired power output required to maintain performance (Vercruyssen & Brisswalter, 2010). Thus, it is reasonable to presume that optimal cadence will differ among individuals based on fitness level, as well as differences in their metabolic, anthropomorphic and neuromuscular composition (Vercruyssen & Brisswalter, 2010). This was true of our participants, as there was a large range in the preferred cadence rates (see Table 2.1).

Research has demonstrated a difference between the energetically optimal cadence and the freely chosen cadence within individuals. Studies suggest that for short duration exercise the energetically optimal cadence is between 55-65 RPM while the freely chosen cadence is 80-95 RPM (Marsh & Marlin, 1993; Whitty et al., 2009). Marsh & Marlin (1993) demonstrated that aerobically fit subjects have an energetically optimal cadence in the range of 55-65 RPM, similar to the self-selected cadences seen in the participants in this study. However, Marsh & Marlin's (1993) subjects had self-selected cadences in the range of 90-100 RPM, much higher than the majority of the participants seen here. This could be the result of their participants being elite cyclists while the participants in this study were not. It could also be the instructions given to participants. Participants in this study were asked to pedal at a rate that they felt they would be able to comfortably maintain for a 30 minute exercise bout. This may have artificially lowered their self-selected cadence in the familiarization session due to their knowledge of their own fitness, their familiarization with cycling, and their general expectations of the exercise.

Studies have shown that individuals are able to maintain a higher freely chosen cadence during a 30 minute exercise bout, however, the stability of this cadence pattern decreases as the duration of the exercise increases, such that freely chosen cadence will shift towards the energetically optimal cadence after prolonged cycling at a constant power requirement (Vercruyssen & Brisswalter, 2010). This may partially explain why individuals cycled at a higher cadence rate during the constant power session. Another potential reason for increasing freely chosen cadence at a given power output may be due to the influence of the inertial load on the pedal crank, and individuals may have been trying to decrease neuromuscular fatigue influenced from this load of the crank (Vercruyssen & Brisswalter, 2010). This may have been a factor due to the bike that was chosen for this study. This study implemented a recumbent bike rather than a spin bike, as the long term goal of this venture is to examine an exercise-navigation dual-task paradigm in clinical populations. Clinical populations are more likely to use equipment that can support their trunk and reduce the need to maintain postural stability (Sibley et al., 2008). However, younger adults may be more likely to ride either a) and actual bike, or b) an upright spin bike rather than a recumbent bike. This in turn may have also impacted their self-selected cadence as well as the variability in their cycling cadence.

Variability within biological systems enables these systems to be flexible and to make adaptations based on afferent feedback from internal and external stimuli (Warlop et al., 2013). Rhythmical movements, such as cycling and walking, are dynamic and complex tasks that use sensorimotor information in order to successfully adapt to the environment

(Warlop et al., 2013). Cycling, unlike walking, is far more constrained with respect to the biomechanical parameters of the movement. The motor patter of the movement is largely determined by the bike itself – the design of the seat and the angle at which the legs reach the pedals, as well as the movement amplitude of the cycling pattern (Warlop et al., 2013). Additionally, cycling reduces the amount of trunk stability required when compared to walking and does not require balancing on a single limb, nor does it require anticipatory or compensatory postural adjustments (Warlop et al., 2013). The need to maintain trunk control would have been further still reduced in our study as participants were seated on a recumbent cycle ergometer, thus providing more support to the trunk than a typical spin bike. Variability in cadence during recumbent pedaling in this task could be linked to variation in speed control that is either intentional (e.g. slowing down to navigate or slowing down due to fatigue) or unintentional (e.g. lack of attention to speed control or variation in single cycle neuromuscular control).

Participants pedalled at their freely chosen cadence, rather than maintaining a specific pedal rate. This was done for numerous reasons. First and foremost, this strategy was chosen to allow examination of naturalistic cycling behaviour and resultant movement and physiological parameters. Second, people have different natural cadences; forcing people to pedal within a specific cadence range arguably increases executive load. Executive load may be increased two ways: 1) it increases the load of visual feedback as now participants would be asked to monitor their RPM on the exercise machine itself, and 2) pedalling at a rate that is unnatural may also require more top down executive control to pedal outside of their own energetically optimal cadence and / or freely chosen cadence to maintain a specific cadence. Thus, this design provided insight into natural changes to mean cadence and cadence variability, and increased ecological validity. Warlop et al. (2013), examined differences in autocorrelations in cycle time between two conditions: a freely chosen cadence and a constrained cadence of 60 RPM. They recruited 15 male participants and to complete 10 minutes of cycling at a 10 Newton (1Kilopascal) work rate for a 2 minute warm up followed by 10 minutes of cycling in one condition, followed by a rest period, and then 10 minutes of cycling in the other condition (Warlop et al., 2013). They found that there was a significant difference between the constrained condition of 60 RPM vs. a freely chosen cadence (which was approximately 82 RPM), but that the variability as measured by standard deviation and coefficient of variation, was not significantly different (Warlop et al., 2013). The authors do note, however, that while there may be no difference in variability, the metrics of the movement were different, such that cadence was smoother in the freely chosen cadence condition vs. the constrained condition (Warlop et al., 2013). The authors therefore suggested that imposing a specific cadence on individuals may lead to disturbances in one's ability to control the variability in the pattern of rhythmic movement, resulting in a less adaptable cycling pattern (Warlop et al., 2013).

Cycling outdoors would require executive resources in order to monitor other traffic, road signs and pedestrians. Additionally, executive resources would be required to perform the navigation of the cycling route, and updating of the individuals' place within the route (Lövdén et al., 2007; Wiener et al., 2009). This study manipulated the executive load of individuals on a stationary bike by having them perform the visual search task, explore and navigation tasks.

Due to the difficulty of the Google Earth tasks and the associated executive load, it is likely that individuals pedalled slower and more variably so as to extract salient features from their environment. As in natural navigation, people will move more slowly, and potentially even stop to examine features of buildings and / or street signs at decision points before making a turn (Lövdén et al., 2007; Wiener et al., 2009). These changes to cadence were responsible for the differences in the power output of the individuals, as they began to pedal slower during the navigation tasks. Future studies should examine the features of the variability with respect the features of what is happening in the virtual environment of Google Earth. During navigation tasks, multiple executive domains are required: attention, visuospatial working memory, planning and decision making to name a few (Bates & Wolbers, 2014; Lövdén et al., 2007). With a more complex environment provided from Google Earth compared to the 'simplistic' visual search task, more features need to be extracted from the scenery of the task in order to perform the task correctly.

One of the concerns at the outset of the study was that, if people do slow their cadence and become more variable, they may slow to the extent that their heart rate would fall below the target heart rate zone, minimizing aerobic benefits of exercise. On average, participants were able to maintain their target heart rate, despite having no feedback on heart rate itself. Heart rate was slightly higher at the end of the exercise as observed in the second cycle only and visual search task blocks. This could be due to participant fatigue approaching the end of exercise, which is partially supported by the RPE data, as RPE was higher in VST-EXE 2 compared to VST-EXE 1. However, there was no difference in RPE between CYCLE 1 and CYCLE 2. Therefore, the higher RPE may be partially attributed to possible differences in RPE over time when engaged and not engaged in an executively demanding task. Another possible explanation is that the familiarization session, where it was determined what work rate would elicit the target heart rate, was not long enough.

Work rate was increased every two minutes until the target heart rate was achieved, possibly underestimating the work rate necessary to maintain the target heart rate over the course of a 30-minute exercise bout. It is also important to note the difference between individuals with respect to their target heart rate and their average heart rate while exercising in the constant resistance condition. Some individuals were below their target heart rate, some were close to their target heart rate and some were well above their target heart rate. Again, this could be due to the difference in exercise duration between the familiarization session and the 30-minute exercise bout. However, it could also be due to differences in perception of workload when performing a dual-task. Therefore, while the average heart rate was at or above the target heart rate of the group, differences between individuals do suggest the need for heart rate monitoring either by the participant themselves, by the researcher, or therapist employing the exercise.

The purpose of collecting individuals on the constant power setting was to examine possible changes to heart rate. Constant resistance settings afford power output and resultant heart rate to vary with respect to cadence at the specific resistance level. If participants were unable to maintain heart rate in the constant resistance setting, but were able to maintain heart rate in the constant power setting, then it may speak to the need for equipment that has constant power capabilities. The main effect of seeing a higher overall cadence in the constant power setting is therefore likely due to participants pedalling faster in order to experience a lower resistance against the fly wheel of the bike. This is also likely why variability was higher in the constant power setting; slowing the pedalling cadence on the bike then increased the resistance, making it more difficult to pedal. This may be a marker of transient changes in attention towards the exercise task, either because participants are more engaged in the executive task or because they are mind wandering during the cycling alone tasks (Voss et al., 2013).

Interestingly, heart rate was not different between the constant resistance and constant power settings as was anticipated. This finding positively supports the notion that young health adults are able to maintain a desired work rate on standard equipment that does not have constant power capability. Again, heart rate increased at the end of exercise for both constant power and constant resistance settings, and this may be due to the aforementioned issues with choosing the heart rate values.

2.8 Conclusions

This study provides support for the idea that it is feasible to concurrently couple aerobic exercise (in this case stationary cycling) with secondary executive tasks without compromising the maintenance of the exercise. The study results reinforce the importance of measuring heart rate to ensure that participants are maintaining the aerobic component of the exercise during the performance of the navigation and exploration tasks. Future work will aim to examine both the behavioural performance of the exercise itself, as well as performance on the virtual navigation tasks using Google Earth, and what dual-task trade-offs occur when this task is performed in young healthy adults. This will help to guide and inform future exercise-executive paradigms that are combined in a concurrent manner.

Chapter 3: Study 2

Examining Factors Influencing Task Challenge during Virtual Navigation

3.1 Introduction

Maintaining or improving executive function has become a prominent area of research as the population ages. Aging is associated with an increase in the prevalence of age related decline in executive function, as well as an increase in the prevalence of other neurological disorders that effect executive function, such as dementia, MCI, AD and stroke (Erickson et al., 2013; Raz & Rodrigue, 2006). Executive training paradigms are one means of improving executive function in a variety of age groups and clinical populations. This can occur informally, through social interaction and participating in activities that are demanding of executive function, such as crosswords or card games, or can occur more formally through rehabilitation or scientific interventions (Kelly et al., 2014). While this method is effective at improving function in the executive domain that was trained, transfer effects to improvements in other domains range from modest to no transfer at all (Binder et al., 2015; Kelly et al., 2014; Reijnders et al., 2013). Additionally, minimal to no transfer effects are seen from improvements on clinical / scientific metrics of executive function to improvement in everyday function as assessed from activities of daily living (ADLs) (Kelly et al., 2014).

Aerobic exercise has emerged as a means of maintaining or improving executive function across the lifespan, from children to older adults to clinical populations (Hillman et al., 2012). Aerobic exercise participation has shown improvements to various behavioural outcome measures of executive function, including: Flanker task performance, Trails A & B performance, and the Digit Span task performance (Anderson-Hanley et al., 2012; Kamijo et al., 2007). Aerobic exercise has also shown improvements to various physiological measures of executive function, including: positive changes to the P3 event related potential, brain volume changes as measured with MRI, and improvements to white and grey matter integrity (Colcombe et al., 2006; Erickson et al., 2011; Kamijo et al., 2007).

A subset of aerobic exercise, referred to as 'exergaming' by many, has emerged in the literature as a novel approach for combining aerobic and executive training into a concurrent task challenge. Exergaming can be implemented using interactive videogame systems such as Dance Dance Revolution® and Nintendo Wii™, or can be implemented using traditional aerobic exercise equipment further equipped with a screen or a separate display, enabling participants to interact with the secondary task (O'Leary et al., 2011). Many of the studies examining exergaming interventions have shown improvements to measures of executive function (Anderson-Hanley et al., 2012; Grealy et al., 1999). Limitations of these studies, however, are that the parameters of the exercise, such as ability to maintain cardiovascular work rate during performance of the game or the potential impact of exercise on behavioural changes, have not been examined. While improving executive function is important, it is equally important for participants to improve or maintain cardiovascular capacity, as this is a primary goal of aerobic exercise participation (Wilson et al., 2016). Ultimately, the objective should be to provide a task that demands an appropriate challenge from both executive and physical functions. To that end there is a need to understand, and potentially minimize, the likely trade-offs that may occur when performing concurrent tasks during aerobic exercise. The goal of the current work is to advance the development of a paradigm that couples physical exercise and an executive task that a) challenges the cardiovascular system to meet target exercise intensity, b) engages executive domains at an intensity that promotes compliance, and c) engages executive tasks that challenge multiple domains of executive function to transfer to cognition globally and has ecological validity in order to promote transfer effects to activities of daily living (Tait et al., 2017).

Concurrently coupling aerobic cycling with virtual navigation may meet the above criteria. Cycling is a predominant means of improving cardiovascular capacity in numerous populations, and is an aerobic exercise that is suited to multiple fitness levels, ages, and clinical populations (Billinger et al., 2014; Sibley et al., 2008). Navigation is defined as the process of traversing from an origin to a destination while performing a locomotor activity requiring sensorimotor input (Wiener et al., 2009) Navigation is a dynamic and complex task that requires the simultaneous use of multiple executive domains including: visuospatial skills and visuospatial working memory, working memory, attention, decision making and planning (Moffat, 2009; Wolbers & Hegarty, 2010). Navigation is also required for the performance of everyday activities in order for us to interact with our environment, and is a skill that is known to decline with age and neurologic injury or degeneration (Bates & Wolbers, 2014; Moffat, 2009; Spiers & Maguire, 2008). Everyday environmental interaction requires the individual to perceive their environment and to engage multiple executive domains so as to successfully reach a destination of interest (and potentially return to the point of origin), to avoid obstacles (such as other people), to monitor flow of traffic and pedestrians, and to obey traffic signs and lights (Epstein & Vass, 2014). Therefore, the proposed task of creating a concurrent exercise-executive challenge, by coupling aerobic cycling with virtual navigation, may have the potential to promote transference of improvements to other executive domains that may impact activities of daily living.

While virtual navigation is considered a potentially useful concurrent task during exercise, the initial challenge is determining and regulating task difficulty of the virtual navigation task itself. A task that is too easy likely does not stimulate the executive demands necessary for meaningful benefits (Basak et al., 2008). Similarly, a task which is too difficult will likely lead to either poor compliance to or and abandoning of either the navigation or exercise during dual-task performance (Boksem & Tops, 2008). This means that the task has to be challenging enough to engage the person and require the use of executive resources (i.e. not boring), but also should not be so difficult that it requires an abundance of executive resources, thus funneling resources away from the requirements of the exercise, nor being so difficult so as to cause frustration on the part of the participant (Boksem & Tops, 2008). Ideally, the design of the navigation task should allow the researcher or clinician to increase navigational task difficulty as individual performance improves. This in turn would allow for an optimization of task difficulty within a person over the course of a research or rehabilitation intervention, especially as individual differences in navigational ability may also contribute to perceived differences in task demands.

If one is to couple the virtual navigation task with a bout of aerobic cycling exercise, then the navigation task should likely be introduced during the cardiovascular portion of the exercise, outside of the time taken for the individual to warm up and cool down, to optimize the potential additive effect of exercise-executive training to executive function as well as to optimize aerobic performance. The availability of commercial programs that digitally render cities (real or virtual) now make it possible to virtually navigate through a wide variety of environments from a first-person perspective. While there are no standard approaches to control difficulty of the navigation task there are there are numerous options for adjusting task challenge within a virtual navigation task. The first way to achieve differences in task challenge is to manipulate the required number of directional changes (turns) individuals must make while finding their way in a virtual space. Presumably, the more directional changes that individuals are required to learn, the more difficult the task will be as the demands placed on working memory increase (Gallotti et al., 2016). In addition to manipulating the number of turns, manipulating the number of visual markers outlining the route as well as the length of the route that individuals are required to learn, both influence navigation performance. Therefore, there is likely a balance between the length of the path and the frequency of the path markers (Gallotti et al., 2016). Another factor that may be of importance during virtual navigation performance is the layout of the virtual environment (Lövdén et al., 2007). Many North American cities have a grid-like road layout. Conversely, many European cities have much more complicated road layouts, and in many cases have no discernable patter. For example, London taxi drivers take between 2-4 years to train and learn the layout of the city before they can become fully licensed cab drivers (Maguire et al., 2000). Therefore, choosing the environmental layout also needs to be considered in conjunction with the number of turns and the overall path length of the route (Lövdén et al., 2007; Maguire et al., 2000).

There are multiple benefits to using a virtual environment to challenge executive function. One of these benefits is that there are no physical consequences to poor navigational performance or getting lost in the environment entirely (Pedroli et al., 2018;

White et al., 2018). An additional benefit of virtual reality is the malleability of the environment(s) by the researcher or clinician, enabling one to manipulate the route for based on the ability of the individual, as well as based on the task demands addressed above. Lastly, as virtual platforms continue to emerge and improve, it may be possible to have clinical participants perform a virtual navigation task within their home neighbourhood or surroundings, thus further increasing ecological validity, and hopefully improving their ability to live independently. This in turn may help to promote adherence to the rehabilitation program as the movements are seen as more purposeful and combine the added mental health benefits of providing individuals with access to more naturalistic and nature-like environments (Valtchanov & Ellard, 2010; White et al., 2018).

In order to address the above criteria, it was proposed that Google Earth could be used as a platform for virtual navigation. Google Earth is a free internet platform that enables individuals to freely create routes within the program and allows the collection of navigation performance by way of recording the global positioning coordinates in latitude and longitude at a rate of two samples per second. Additionally, as the visualization of Google Earth improves, individuals will hopefully be able to practice navigation around their own neighbourhood, which is especially beneficial for clinical populations. Finally, while there are current programs that enable participants to engage in navigation tasks, these programs may not be as executively engaging as Google Earth. Many programs have pre-determined routes and paths for one to follow, meaning individuals are path following rather than wayfinding. Thus, Google Earth may promote an environment that is more akin to the recruitment of executive resources in real-world navigation tasks compared to other software programs.

In addition to the task related factors that influence navigation performance, there are also individual factors that likely influence performance of virtual navigation tasks. Sex differences have been well documented in the literature, with males outperforming females on navigation tasks (Lövdén et al., 2007; Wolbers & Hegarty, 2010). The Google Earth platform is similar in graphics to that of a first-person videogame. Therefore, it is likely that amount of video game play, and type of video game play, influence virtual navigation performance (West et al., 2015). Additionally, individual navigational experience likely has implications for virtual navigation performance. Active navigation via driving or cycling, passive navigation (i.e. being a passenger) in a vehicle or on public transportation, and reliance on global positioning systems may influence one's ability to navigate in a virtual platform.

Therefore, the objective of this study was to examine task related factors and individual related factors that may influence the task challenge during virtual navigation performance in young healthy adults. This was considered an important first step in order to determine factors needed to control task difficulty prior to concurrently coupling the virtual navigation task with aerobic exercise. In the current study, control of task difficulty was achieved by manipulating the layout of the environment: grid like vs. no discernable pattern, and the number of turns that individuals were required to remember (few versus. many). Navigation performance was measured in terms of overall distance travelled (absolute value), and distance error relative to being able to navigate the route perfectly (relative error). Navigation performance was also measured in terms of time spent navigating, again both in absolute and relative terms, as well as time spend moving forwards, backwards, and turning. With regards to task related factors it was hypothesized that navigation performance would be better on the shorter routes compared to the longer routes, and that navigation performance would be better in the grid like environments when compared to the environments that had no discernable pattern. Navigation performance was also compared to sex, navigation experience and video game play experience. It was hypothesized that: a) males would perform better than females on the navigation task, b) those with higher perceived navigation ability would perform better than those with low perceived navigation ability, and c) that those with more video game play experience would perform better than those with less video game play experience.

3.2 Methods

Participants

Twenty healthy young adults (10 females, 10 males) participated in the study (aged 18 – 34, mean (± sd) age = 23.8 ± 4.3 years, height = 173.6 ± 6.8 cm, and weight = 75.7 ± 12.5 kg. All participants reported their sex and gender to be the same (i.e. sex = female, gender = female). All participants completed the Get Active Questionnaire (GAQ), provided self-reports of educational background, exercise participation level, video game play experience and navigational experience. Participants also had normal or corrected to normal visual acuity (as assessed through the Snellen eye test and the Mars Visual Acuity test), and reported no other visual impairments (e.g. colour blindness) in order to perform the computerized executive tasks and the computerized virtual navigation task. This study received clearance from the Office of Research Ethics at the University of Waterloo, and all participants provided written consent prior to study participation.

Overview of General Experimental Set-Up

Participants attended the lab on a single occasion. Screening for inclusion criteria included: non-smoking, no visual impairments that would alter their ability to perceive the stimuli in the computerized tasks, and not pregnant. Vision was screened using a Snellen eye chart at a distance of 3 meters, as well as using the Mars Contrast Sensitivity test. Participants had visual acuity of 20/20 or better and had binocular contrast sensitivity of 1.64 or better.

Participants first performed the virtual navigation tasks while seated at a desk. The virtual display was projected via a television screen that was 2 meters away from the participant. This set-up was used as future studies would examine virtual navigation while cycling, and this was the equipment and distance that was to be used to couple the two tasks. Then participants completed a custom-made questionnaire regarding their educational background, exercise participation, video game play and navigation ability. Following this questionnaire, participants performed executive tasks on a computer using the online tool PsyTools (https://www.psytoolkit.org/). Executive tasks completed by participants were the following: Wisconsin Card Sorting Task, Stroop Task, Corsi Block Task, Visual Search Task, and a 2-D Mental Rotation Task.

Participant Demographic Questionnaire

Participants completed a demographic questionnaire to attain information regarding their educational background and field of study. There were questions regarding their participation in exercise as well as exercise preferences. Participants also answered questions regarding their videogame play, and how often they navigate as a driver of a vehicle, passenger in a vehicle or driver of a bicycle.

Participants then completed 12 visual analog scales to attain their perception of their videogame playing habits as well as their perception of their navigation ability. The questionnaire can be found in Appendix F. For all scales, a lower value on the visual analog scale represented poorer performance ability or participation in that activity, while higher values represent greater performance or participation. Perceptions for questions relating to navigation ability were combined to create a composite score for Overall Navigation Ability, and perceptions for questions relating to videogame play were combined to create a composite score for Overall Videogame Play Ability. A summary of the demographics questionnaire can be viewed in Table 3.1 below.

Participant Demographic Information

Category	Female	Male
Handedness: Right/Left	8/2	9/1
Program: Kinesiology / Other Science	9/1	8/2
Level of Study: Undergraduate / Graduate	5/5	5/5
Self Reported Exercise Hours / Week: $\bar{X}$ ± s.d	5.1 ± 3.3	5.2 ± 5
Hours per week driving: $\bar{X}$ ± s.d	1.9 ± 2.9	5.6 ± 7.6
Hours per week as a passenger: $\bar{X}$ ± s.d	1.1 ± 1.05	3 ± 4.6
Hours per week on Public Transit: $\bar{X}$ ± s.d	2.7 ± 2.4	1.9 ± 3.4
Self Reported Video Game Player: Yes / No	2/8	5/5
Video Game Preference: Immersive / Non-Immersive	0/2	1/4
Hours per day playing video games: $\bar{X}$ ± s.d	0.1 ± 1	0.7 ± 0.9

Table 3.1: Summary of the findings from the participant demographic questionnaire by sex. Values are means ± standard deviation, or a count between the two categories listed.

Mental Workload Questionnaires

Upon arrival to the laboratory, participants rated their overall level of fatigue using the Rating of Fatigue (ROF) scale (Micklewright et al., 2017). This measure was taken again upon completion of the testing session. Additionally, after each virtual navigation task and after each series of executive tasks, participants completed the NASA Task Load Index (NASA-TLX). The NASA-TLX is a questionnaire that examines mental workload in the following six domains: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration (Hart & Staveland, 1988). These domains are shown along with a prompt statement to assist participants in gauging the question being asked, and beneath each point is a 20 point Likert scale which ranges from “very low” to “very high”, with the exception of the Performance domain, which ranges from “perfect” to “failure” (Hart & Staveland, 1988). Therefore, when the values are summed across the six domains, higher values indicate greater overall perceived workload and poorer performance.

Virtual Navigation Tasks

The virtual navigation tasks were performed using the free download platform of Google Earth in the 3D rendered version of street view. This provided a first person view of movement through the virtual environment. Movements through the environment were performed using a keyboard: up and down arrow keys to move forward and backward, respectively, while left and right arrow keys to make leftward and rightward turns, respectively. Two cities were used for this experiment: New York City (NYC), United States of America, and Florence (FLO), Italy. These cities were chosen to address the potential impact of environmental layout on navigation ability as mentioned previously. New York City is a grid-like pattern of roadways while Florence has many round-a-bouts and no discernable pattern for roadways. Four routes were provided to the participants: few turns in a grid-like city (NYC 4 Pin), many turns in a grid-like city (NYC 8 Pin), few turns in a city with no discernable pattern to road structure (FLO 4 Pin) and many turns in a city with no discernable pattern to road structure (FLO 8 Pin).

For all routes, participants were given a start point, a pin that was placed in the virtual environment and had the number "1" associated with the pin. Participants were positioned to begin navigating in the direction necessary to find Pin 2. Participants were instructed to find Pin 2, and then make their way back to Pin 1. From there, they were to turn around, and then proceed to move from Pin 1, to Pin 2, and then to Pin 3, and again return to Pin 1, connecting through Pin 2. This process was repeated until all pins had been found, and the participant returned to the start position. The routes that had few turns had a total of 4 pins, while the routes with many turns had 8 pins total. Information on the routes themselves can be found in Table 3.2 and topographical views of the routes can be seen in Figure 3.1.

Google Earth Route Information

Route	Ideal Distance (km)	Ideal Time (min)	# Left Turns	# Right Turns	Total # Turns	Mean Distance (m) between Pins	SD Distance (m) between Pins	Ranking of Most to Least Difficult
New York City 4 Pins	4.95	7.86	2	1	3	427.2	93.3	3
New York City 8 Pins	11.84	19.67	3	3	6	347.8	80.2	2
Florence 4 Pins	4.32	7.1	1	2	3	359.0	10.1	1
Florence 8 Pins	8.72	14.43	3	2	5	167.1	19.8	4

Table 3.2: Summary of the Google Earth route information. Total route distance is the total distance the participant would travel if participants completed the task along an ideal route. The number of turns are depicted as the number of turns one would take when travelling from Pin 1 to Pin 4 or 8 a single time, and ceasing the task at Pin 4 or 8.


A
Start
1
2
3
4
Gray Buildings © 2011 CyberCity


B
8
7
6
5
4
3
2
1 Start
Gray Buildings © 2011 CyberCity

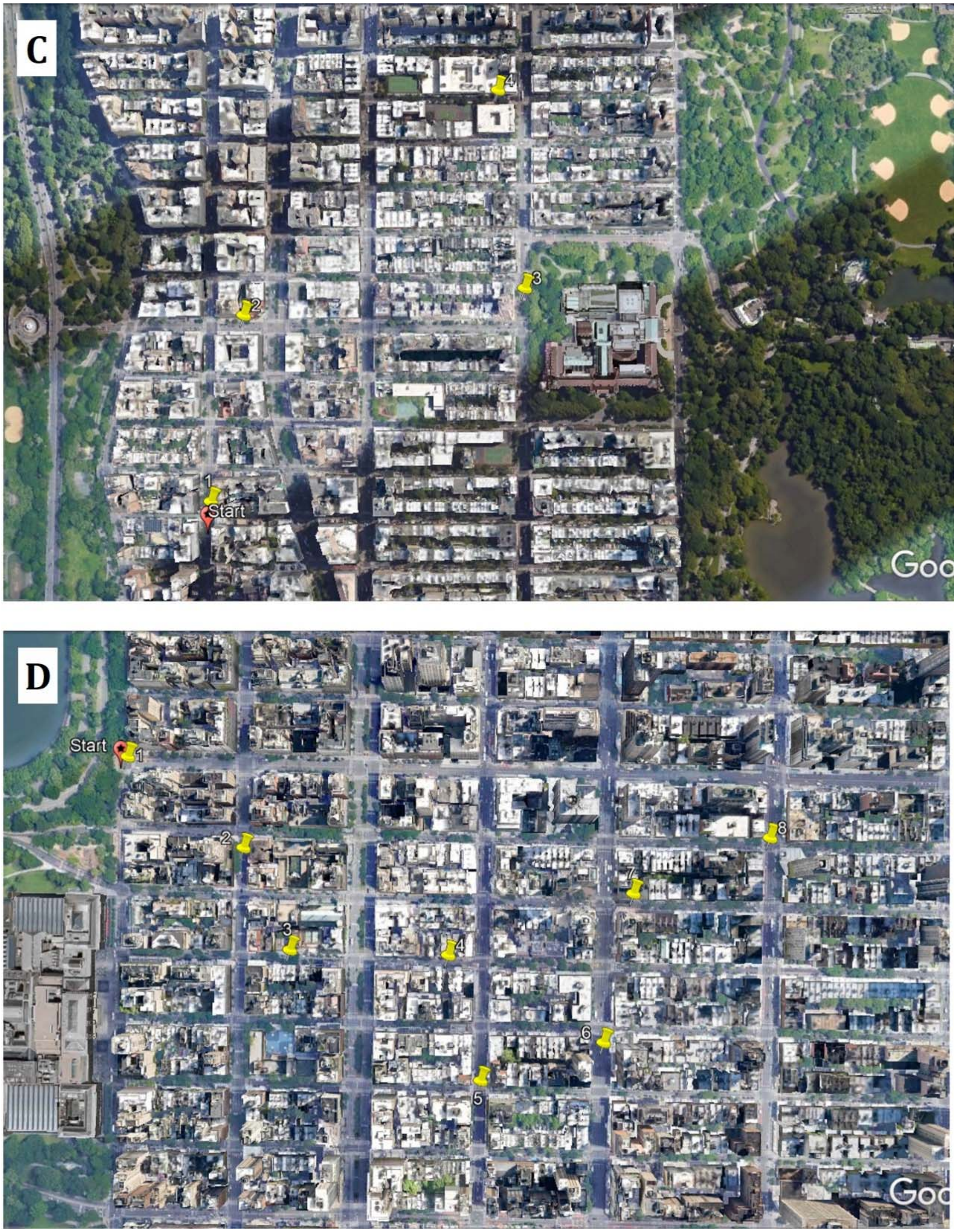


Figure 3.1: Aerial view of Google Earth routes: **A**) Four pin route in Florence (few turns); **B**) Eight pin route in Florence (many turns); **C**) Four pin route in New York City (few turns); and **D**) Eight in route in New York City (many turns).

Executive Tasks

To measure executive function, participants were asked to perform numerous computerized tasks. For these tasks, participants were seated at a desk and the tasks were displayed on a flat panel computer screen (Dell, Round Rock, Texas, USA) that was 0.5 meters in front of them. Participants were to respond to the stimuli by using the keyboard, or the computer mouse, depending on task requirements. Specific participant task instructions, as well as visuals for the executive tasks can be found in Appendix D.

Stroop Task: The Stroop Task is an executive interference task (Weinstein et al., 2012). For this task, one of the words YELLOW, RED, GREEN or BLUE appeared on the computer screen. When the word presented was depicted in its own graphics colour (e.g. word RED in red 'ink') this was termed the congruent condition (Weinstein et al., 2012). When the word presented was depicted in a graphics colour different from its own, (e.g. word RED in blue 'ink') this was termed the incongruent condition (Weinstein et al., 2012). In all conditions, participants were asked to respond to the colour of the graphics (i.e. the 'ink' colour) and not the colour the word was depicting. One block of this task took approximately 2 minutes to complete, and participants completed 3 blocks. This task had 40 trials per block.

Corsi Block Task: The Corsi Block Task is a visuospatial working memory task (Fischer, 2001). For this task, a series of 9 boxes appeared in random positions across the computer screen. Upon the start of the trial, boxes were quickly illuminated, starting with 2 boxes. Participants were asked to then use the mouse to click on the correct boxes, in the order in which they were illuminated (Fischer, 2001). After each successful trial, an additional box was illuminated until participants could no longer replicate the correct order of illumination, or they successfully identified all 9 boxes in the correct order (Fischer, 2001). One block of this task took approximately 2 minutes to complete, and participants completed 3 blocks.

Visual Search Task: Visual search is an important executive task that enables us to find and remember the locations of objects in a complex visual scene (Oei & Patterson, 2013). For this task, a series of capital letter "T"s appeared in random positions on the computer screen. Some stimuli were blue and some were orange, and some "T"s were right-side up while others were upside-down. There were a total of 5, 10, 15 or 20 stimuli on the screen. The target stimulus was an upright orange "T". Participants were asked to respond by hitting the space bar when they saw the target stimulus, and to refrain from responding when they did not see the target stimulus. One block of this task took approximately 4 minutes and participants performed 3 blocks. This task had 50 trials per block.

Wisconsin Card Sorting Task: For this task, four target cards were presented: one red circle, two green triangles, three blue crosses and four yellow stars. A stimulus card was presented in the lower left corner of the screen, and the stimulus card could have any combination of number of items (1-4), shapes, or colours of the shapes. Participants were asked to match the stimulus card to the appropriate target card – and the match may be based on colour only, shape only, or number of items only (Miyake et al., 2000). However, the rules for what constitutes a 'match' change throughout the task, and participants are then required to figure out the new 'match' rule (Miyake et al., 2000). One block of this task took approximately 4 minutes and participants performed 3 blocks. This task had 60 trials per block.

Mental Rotation Task: For this task, participants were shown an initial 2D image of a random shape. Beneath it there were two target images, both of which appear as rotated images of the original image. Participants were asked to identify which rotated image matched the original image (Zimmer, 2008). One block of trials for this task took approximately 2 minutes, and participants performed 1 block, as the images do not change from block to block. This task had 5 practice trials, and then 10 experimental trials for the one block.

3.3 Data Analysis

Data were analyzed using custom built LabView programs (National Instruments, Austin TX, USA). Google Earth allows for the collection of a video file which records positional information twice per second in both latitude and longitude. This file was read into the custom built LabView program, and latitude and longitude values were converted into distance values (in meters) so that the total distance travelled by the individual was calculated. The conversion formula used was:

Latitude at position N_1COS(COS(RADIANS(90-Longitude at position N_1))*COS(RADIANS(90- Longitude at position N_2))+SIN(RADIANS(90- Longitude at position N_1))*SIN(RADIANS(90- Longitude at position N_2))*COS(RADIANS(Latitude at position N_1- Latitude at position N_2)))*6347.

Additionally, the video file also records a time stamp for how long the individual was at each location, and this information was then used to calculate total time travelling throughout each route. Distance error was calculated as distance travelled minus the ideal distance of the route. Time error was calculated as time taken to travel the route minus the ideal time to complete the route.

The demographic questionnaire information and the information from the mental workload questionnaires were manually entered into a worksheet for further statistical analysis. Data from the executive tasks were automatically recorded into worksheets, and were manually combined for further statistical analysis.

3.4 Statistical Analysis

Navigation performance was measured in terms of distance error (km) and time error (min), and was collapsed into route layout (grid routes vs. non-grid routes) as well as collapsed across route length (the 4 pin vs. the 8 pin routes). Sex was also a factor that was included in the analysis. Two-way ANOVAs were used to examine for differences between factors of route layout and sex, and a separate two-way ANOVA examined differences for factors of route length and sex. A one-way ANOVA was used to examine for an overall effect of sex differences on navigation performance with respect to navigation performance error in terms of distance (km) and time (min). One-way ANOVAs were used to examine possible differences in perceptions of route difficulty as assessed through the NASA-TLX questionnaire and the visual analog scale. Pearson correlation coefficients were used to examine navigation performance with respect to perceived navigation ability and videogame play. Tukey's post hoc test was used when necessary. All significant levels were set to $\alpha = 0.05$.

3.5 Results

Navigation Performance Metrics

There was no main effect of layout (grid vs. no grid) ($F_{1,19} = 2.91$ ($p = 0.34$)) and no main effect of sex (male vs. female) ($F_{1,19} = 1.49$ ($p = 0.44$)) on navigation performance error with respect to distance (km). There was an interaction effect of layout and sex ($F_{1,19}$

= 1799.82 ($p = 0.02$)), on the distance error (km) for the performance of the tasks. Post hoc testing revealed that the distance error was statistically different between all four conditions: male/grid layout, male/non-grid layout, female/grid layout and female/-non-grid layout. Mean (± sd) for distance error (km) was 1.78 ± 0.8 for the male/grid layout, 1.84 ± 3.2 for the male/non-grid layout, 2.34 ± 2.6 for female/grid layout, and 1.47 ± 1.3 for the female/non-grid layout routes.

There was no main effect of layout (grid vs. no grid) ($F_{1,19}$ = 11.50 ($p = 0.18$)), no main effect of sex ($F_{1,19}$ = 2.41 ($p = 0.36$)), and no interaction effect ($F_{1,19}$ = 1.45 ($p = 0.44$)) of layout and sex on the time error (min) for the performance of the navigation tasks. Mean (± sd) time error (min) was 1.32 ± 1.7 for male/grid layout, 4.44 ± 6.9 for male/non-grid layout, 4.82 ± 4.4 for female/grid layout and was 5.06 ± 4 for female/non-grid layout. These results can be seen in Figures 3.2 and 3.3 below.

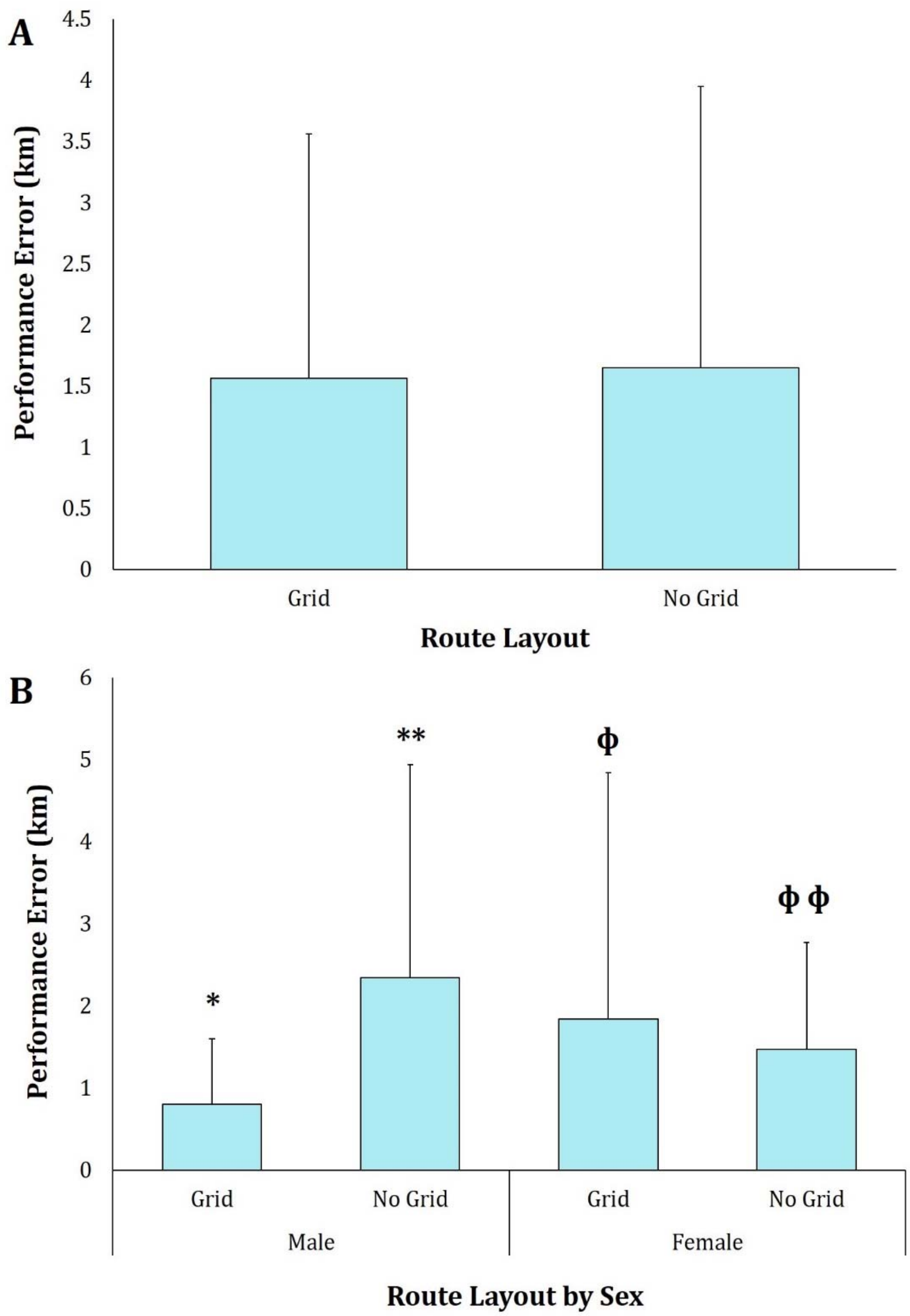


Figure 3.2: Comparison of city layout (grid vs. no-grid) and sex (male vs. female) on navigation performance with respect to distance error (km) ± sd. **A**) Navigation performance error as a factor of layout only; **B**) Navigation performance error as a factor of layout and sex. Here we see that performance was different between all 4 factors / conditions; * $p < 0.05$, ** $p < 0.05$, ϕ $p < 0.05$, and ϕϕ $p < 0.05$.

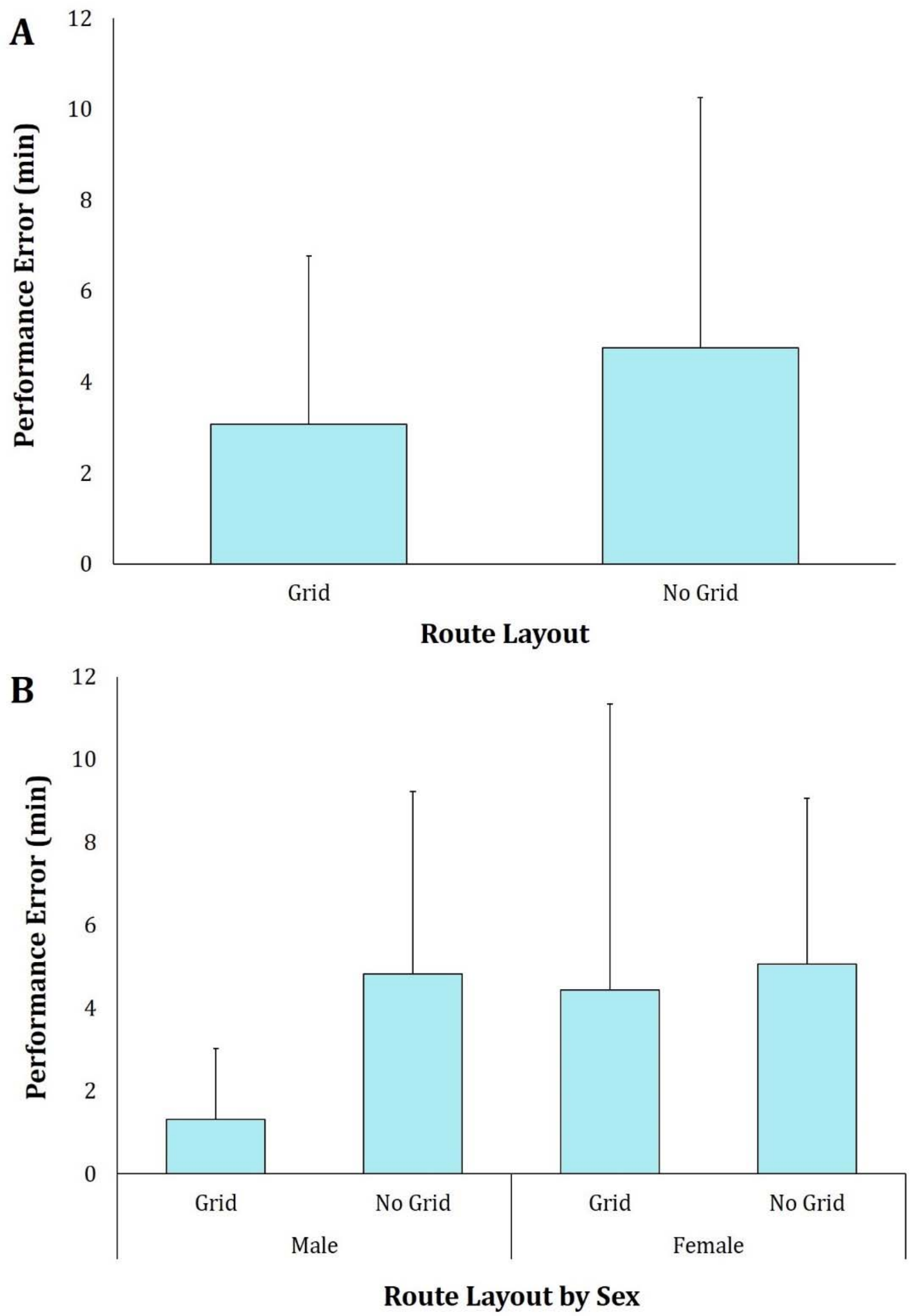


Figure 3.3: Comparison of city layout (grid vs. no-grid) and sex (male vs. female) on navigation performance with respect to time error (min) ± sd. **A**) Navigation performance error as a factor of layout only; **B**) Navigation performance error as a factor of layout and sex.

Navigation performance was also examined with respect to route length, and therefore data was collapsed within the 4 pin and 8 pin routes. When examining factors of route length (4 vs. 8 pin) and sex (male vs. female) with respect to distance error (km), there was no main effect of route length (4 vs. 8 pin) ($F_{1,19} = 0.22$ ($p = 0.72$)), no main effect of sex ($F_{1,19} = 1.49$ ($p = 0.44$)), and no interaction effect between route length and sex ($F_{1,19} = 7.92$ ($p = 0.22$)). Mean (± sd) distance error in km was 2.18 ± 3.2 for male/4 pin, 0.44 ± 0.3 for male/8 pin, 2.37 ± 2.4 for female/4 pin and was 1.44 ± 1.4 for female/8 pin route. With respect to time error (min) there was no main effect of route length (4 vs. 8 pin) ($F_{1,19} = 0.01$ ($p = 0.93$)), no main effect of sex ($F_{1,19} = 2.41$ ($p = 0.36$)), and no interaction effect of route length and sex ($F_{1,19} = 10.26$ ($p = 0.19$)). Mean (± sd) time error in minutes was 5.55 ± 7.1 for male/4 pin, 6.74 ± 5 for male/8 pin, 0.21 ± 0.3 for female/4 pin and was 3.14 ± 2.4 for female/8 pin route. See Figures 3.4 and 3.5.

In comparing sex and navigation performance when collapsed across all tasks, a one-way ANOVA revealed no effect of sex on distance error (km) ($F_{3,76} = 1.49$($p = 0.44$)) or time error (min) ($F_{3,76} = 2.41$ ($p = 0.36$)). Mean (± sd) navigation performance for distance error (km) was 0.65 ± 1.6 for males and 0.95 ± 1.4 for females. Mean (± sd) navigation performance for time error (min) was 1.44 ± 3.8 for males and 2.47 ± 2.8 for females.

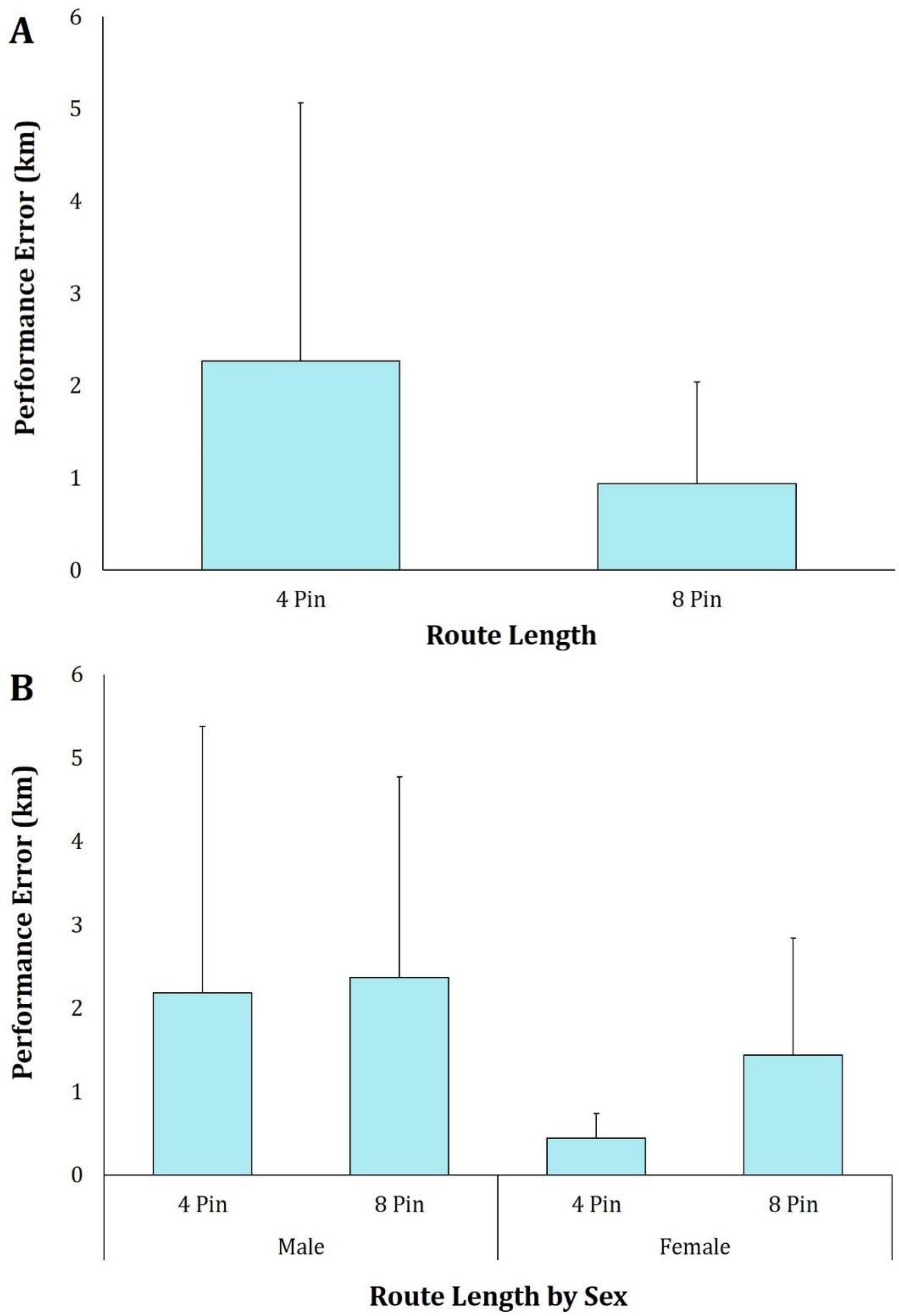


Figure 3.4: Comparison of route length (4 pin vs. 8 pin) and sex (male vs. female) on navigation performance with respect to distance error (km) ± sd. **A**) Navigation performance error as a factor of route length only; **B**) Navigation performance error as a factor of route layout and sex.

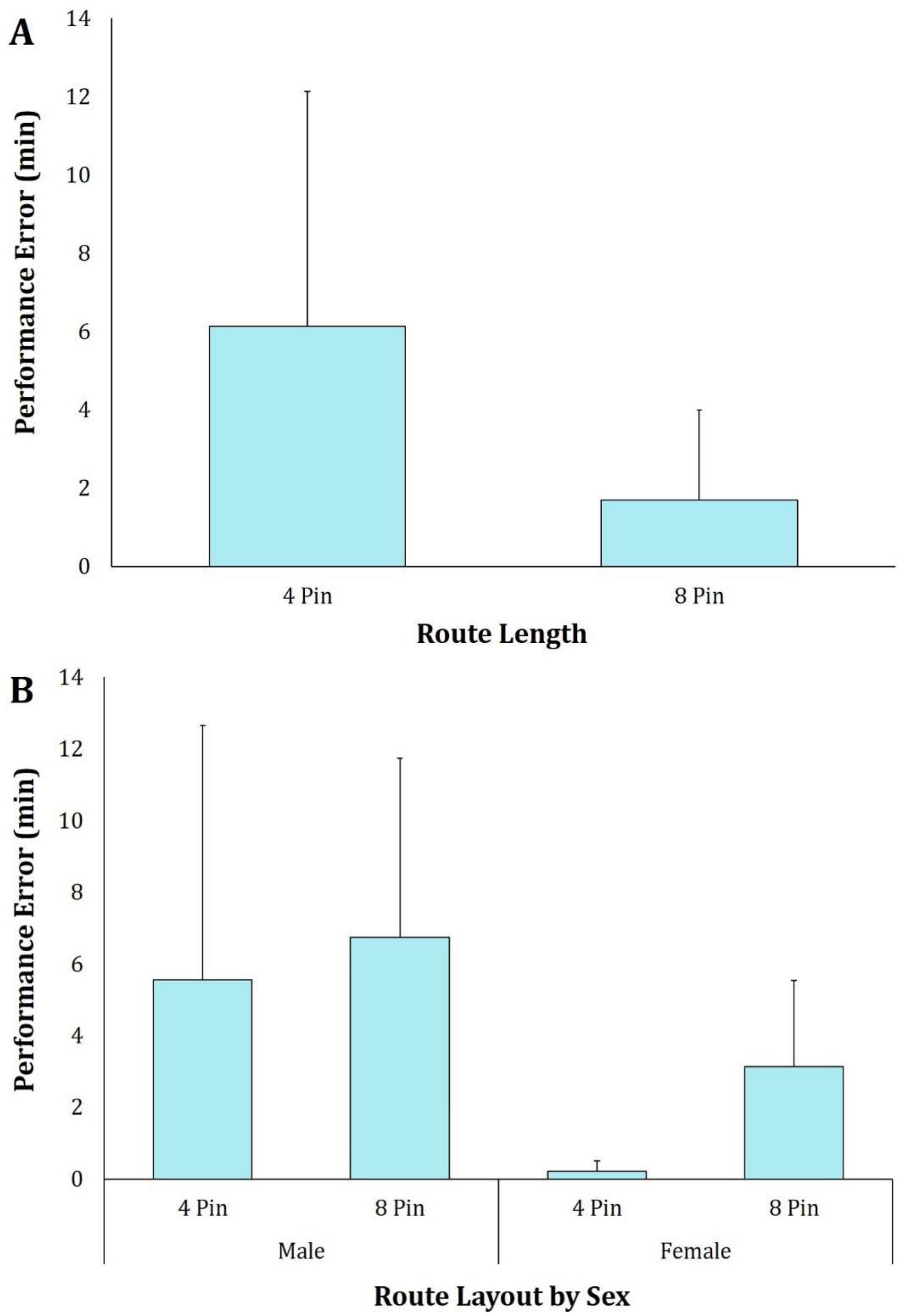


Figure 3.5: Comparison of route length (4 pin vs. 8 pin) and sex (male vs. female) on navigation performance with respect to time error (min) ± sd. **A**) Navigation performance error as a factor of route length only; **B**) Navigation performance error as a factor of route layout and sex.

Psychological Metrics of Navigation Performance

The NASA-TLX contains six separate domains in order to assess perception of task difficulty. These individual domain scores are then summed to give a total difficulty score for each task. The mean (± sd) scores for the NASA-TLX sum scores were 25.4 ± 17.9 for the NYC 4 pin route, 29.2 ± 16.7 for the NYC 8 pin route, 35.9 ± 15.5 for the FLO 4 pin route and was 20.4 ± 14.1 for the FLO 8 pin route, as seen in Figure 3.5 below. There was no statistically significant difference in sum scores within the NASA-TLX between the four separate routes used for this study ($F_{3,72} = 0.92$ ($p = 0.53$)).

Data from the visual analog scales were also compared in order to assess differences in task difficulty perception between the navigation tasks. The mean (± sd) scores for the visual analog rating scores were 3.5 ± 2.2 for the NYC 4 pin route, 3.4 ± 2.1 for the NYC 8 pin route, 4.0 ± 2.1 for the FLO 4 pin route and was 2.3 ± 1.7 for the FLO 8 pin route. Data were compared with respect to route, as well as block order of presentation of each route. There was no main effect for route ($F_{3,48} = 0.65$ ($p = 0.63$)), no main effect of block order ($F_{3,48} = 0.77$ ($p = 0.58$)), and no interaction effect ($F_{9,48} = 0.73$($p = 0.68$)).

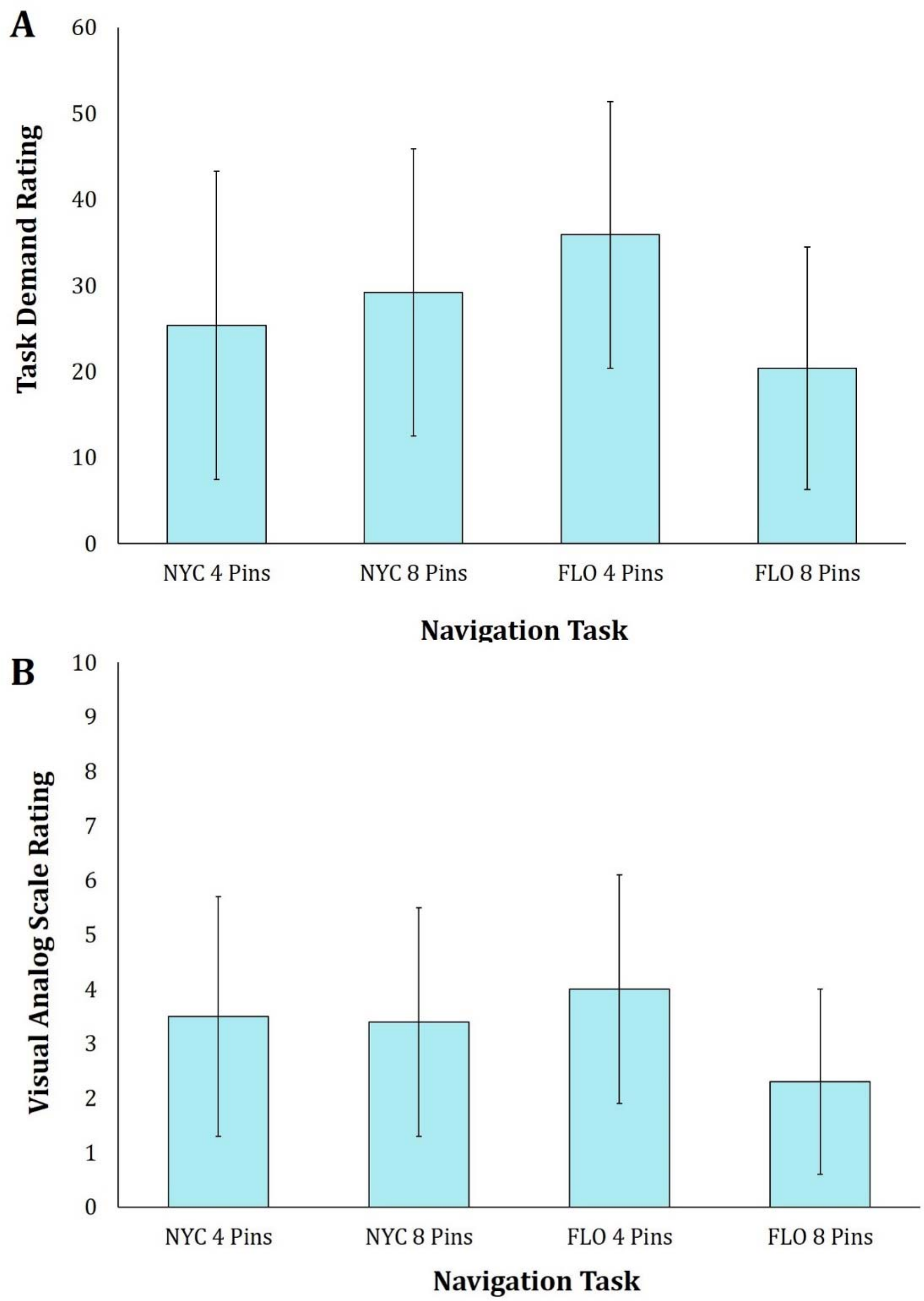


Figure 3.6: A) Average ± sd NASA TLX Sum Scores (a sum of the scores from each of the six domains within the survey) by task **B**) Average visual analog rating scale scores by task (note that the maximal score for the VAS was 10).

Relationship between Navigation and Executive Performance

As a secondary analysis, this study examined if there was a relationship between navigation performance metrics and performance on different executive tasks. Participant performance for each task was averaged across the blocks of trials to produce a final score for each participant. Participants were then ranked from 1-20 based on performance within each task. Then, their overall executive rating was calculated by summing together the rank scores within a participant across each of the executive tasks. This ranking system was also done for the navigation performance metrics of distance error and time error, and again the scores were summed across the two domains for a final navigation score. For both the executive task performance and the navigation task performance, a ranking of 1 indicated best performance while 20 indicates worst performance within the group. Therefore, the lower the sum score, the higher the individual's overall performance within the group. These scores can be viewed in Table 3.3.

Correlational analysis revealed that there were no statistically significant relationships between ranking of individual executive task performance and sum navigational performance. The exception to this was seen in the Corsi block task, as performance on this task was approaching statistical significance with respect to the relationship with navigation performance. When comparing the sum navigation error rank order to the individual executive task rank orders, the correlation and significance values were as follows: 1) card sorting task: $r = -0.09$, $p = 0.71$, 2) Corsi block task: $r = 0.44$, $p = 0.053$, 3) mental rotation task: $r = -0.06$, $p = 0.82$, 4) Stroop task, $r = 0.05$, $p = 0.83$, and 5) visual search task: $r = 0.04$, $p = 0.87$. When comparing the Sum Navigation error rank to the Sum Executive Score rank order, the $r = 0.19$ with a $p = 0.43$.

Participant Executive & Navigation Performance Rank Order

ID	Card	Corsi	MR	Stroop	VS	SUM EXE RANK	Error (km)	Error (min)	SUM NAV RANK
1	17	9	1	14	9	**50**	9	6	**15**
2	16	3	1	16	19	**55**	1	1	**2**
3	14	6	13	3	8	**44**	5	3	**8**
4	13	13	5	6	4	**41**	12	9	**21**
5	10	3	5	9	20	**47**	18	17	**35**
6	15	17	5	8	13	**58**	10	8	**18**
7	20	6	20	4	10	**60**	11	14	**25**
8	9	15	1	17	2	**44**	16	15	**31**
9	2	9	17	10	12	**50**	13	12	**25**
10	2	3	5	11	15	**36**	3	2	**5**
11	6	15	5	15	18	**59**	20	20	**40**
12	10	9	5	7	14	**45**	15	16	**31**
13	18	6	13	18	5	**60**	14	11	**25**
14	8	18	17	12	6	**61**	8	5	**13**
15	1	18	17	1	16	**53**	7	13	**20**
16	18	2	5	20	3	**48**	6	10	**16**
17	5	13	1	2	1	**22**	19	18	**37**
18	10	18	13	19	17	**77**	17	19	**36**
19	6	1	13	5	11	**36**	2	4	**6**
20	4	9	5	13	7	**38**	4	7	**11**

Table 3.3: Rank order scores by participant by task. Card = card sorting task, Corsi = Corsi block task, MR = mental rotation task, Stroop = Stroop task, VS = Visual search task, Error (km) = navigation performance error by distance, and Error (min) = navigation performance error by time. SUM EXE RANK = sum score ranking across the 5 executive tasks and SUM NAV RANK = sum score ranking across the 2 navigation performance metrics. In all cases, the lower the rank value, the better the performance on the given task.

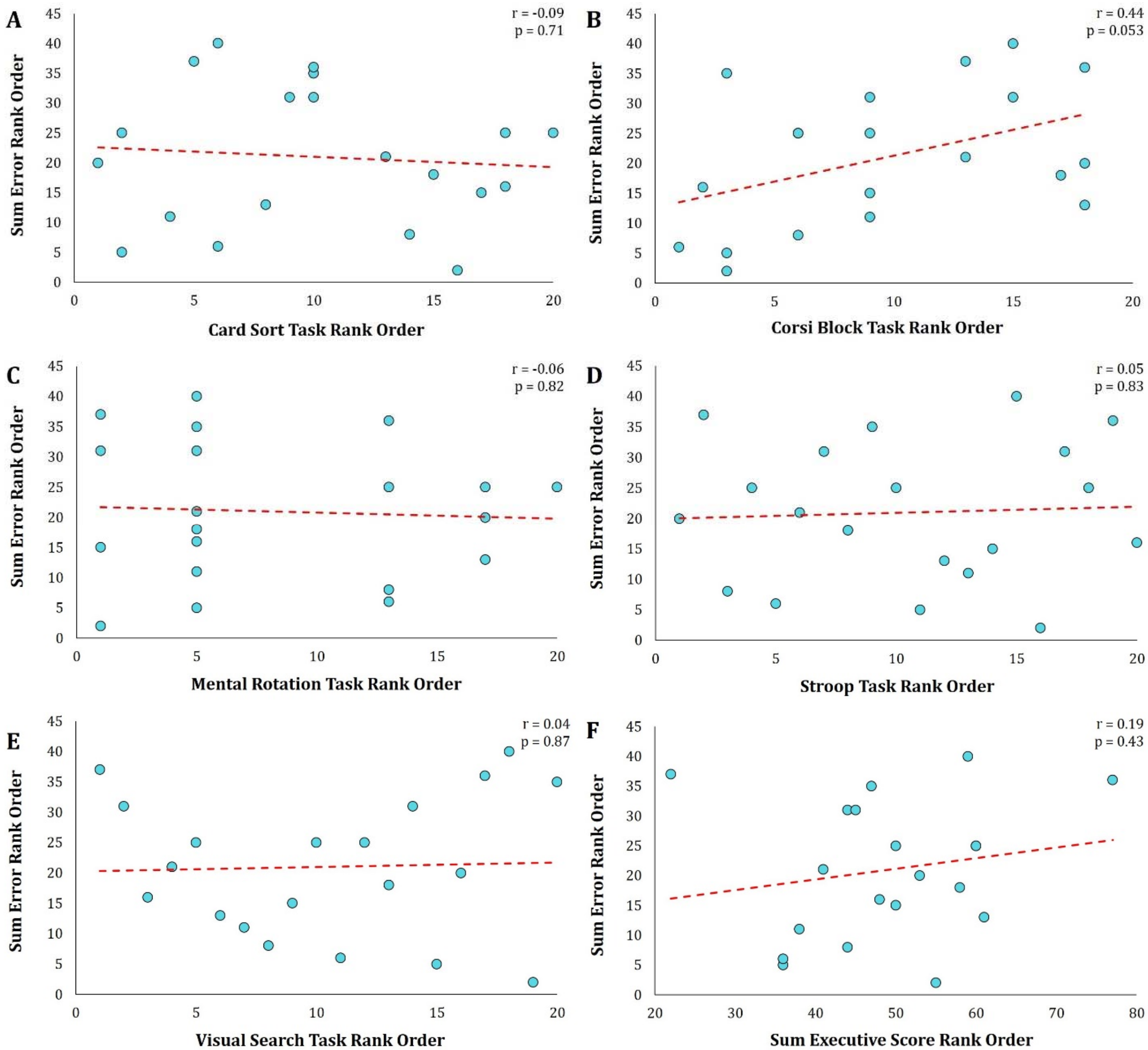


Figure 3.7: Correlational data comparing Sum Navigation Error rank score (Y-axes) to the different executive tasks of **A**) Card Sorting, **B**) Corsi Block, **C**) Mental Rotation, **D**) Stroop, **E**) Visual Search Task, and **F**) Sum Executive Task scores rank order.

3.6 Discussion

The objective of this research was to examine task and individual related factors that may influence an individual's ability to perform a virtual navigation task designed and implemented using the platform of Google Earth. Contrary to the hypothesis, and the majority of the scientific literature, there was no effect of sex on the navigation performance metrics that were examined with respect to the virtual navigation tasks used in this research. There was also no effect of route length, between the 4 pin and the 8 pin routes, and there was no effect of route layout between a grid like city (New York City) and a non-grid like city (Florence). The findings regarding route length and route layout were also contrary to the hypotheses surrounding these factors.

Previous work examining sex differences between males and females have revealed that males outperform females on a variety of navigation tasks, including pencil and paper tasks, virtual reality tasks, and real world tasks (Lövdén et al., 2007; Wolbers & Hegarty, 2010). Lövdén et al. (2007) had participants navigate through different layouts of a virtual musem while simultaneousy walking on a treadmill which was linked to the forward motion of the participant in the virutal environment. They found that when the navigation occurred in a grid-like environment, men traversed a significancly shorter distance to reach the objective location as compared to women. However, sex differences were not apparent when participants were required to reach their objective location within a non-grid like environment (Lövdén et al., 2007). While the results of the current study did not reach statistical significance, the same pattern of results was found here. Males outperformed females in the grid-like environments, whereas there was little difference in performance between the sexes on the non-grid like environments (see Figure 3.3 B). This may be partially explained by the differences in video game play and driving habits between the two sex groups who participated in this study. Half of the male participants reported playing video games while only 20% of the female participants reported playing video games. Furthermore, the female participants who reported playing video games identified as playing non-immersive type games, whereas their male counterparts predominately reported playing immersive type games. It is possible that differences were not seen between the sexes due to a sense of competitiveness, curiosity and mastery of the task (Terlecki et al., 2011). Terlecki et al. (2011) surveyed more than 2000 undergraduate students at an American university and found that while males tended to prefer sports games, women tended to prefer racing games which is analogous to the type of task used here. They also reported that almost all of the post-secondary students surveyed in their study reported having played video games at least once at some point in their lifetime (Terlecki et al., 2011). While their study may have sex differences based on current video game play, it is likely that most if not all the participants have been exposed to video game play in the past, accounting for similarities in the navigation performance between the sexes.

With respect to driving habits, males in this study reported spending more hours per week as both drivers of vehicles and passengers in vehicles, compared to their female counterparts. Therefore, it is possible that the better performance in non-grid like cities for the male participants in this study is due to increased weekly “navigation time” of video games and transportation when compared to the female participants in this study. As a result, route layout will likely be an important point of consideration when designing virtual navigation tasks to concurrently couple with an aerobic challenge, so as not to unduly favour performance of the task based on sex, and to avoid increasing mental task demands and frustration levels on the part of female participants. However, no sex differences in the virtual navigation task used in this study may suggest that this task may be effective at challenging the executive functions of both male and female participants without undue favoritism.

The finding that there was no difference in navigation performance metrics with respect to route length was also interesting. It was assumed that there would be greater distance and time errors associated with the longer routes 1) because of the working memory and visuospatial working memory requirements needed to maintain the outline of the route, and 2) because the route is longer there is more distance over which participants could err and make incorrect decisions regarding pin location and turning behaviour (Taillade et al., 2013; Wolbers & Hegarty, 2010). Working memory is a limited capacity system, and it has been suggested that visuospatial working memory capacity may be limited to 3-4 items (Luck & Vogel, 1997). Therefore, it was surprising that participants had similar performance between the 4 Pin and 8 Pin routes. This may have been a result of previous video game play and navigation experience, as both a driver and / or passenger in a vehicle. This could also be due to differing strategies used by participants and how quickly they adapted those strategies. Based on feedback collected upon completion of the navigation tasks, participants were asked if they had any strategies that they used to facilitate their ability to find their way within the virtual environment. The most common responses were to look for salient features within the environment that ensured that they were on the correct route, as well as counting the number of streets that needed to be traversed prior to making a required turn. If participants were able to quickly adopt a strategy that enabled them to be successful at the task, it may speak to the lack of difference in performance between the shorter and longer routes. Also, participants were asked to choose which routes were perceived as more difficult, based on the two factors: 4 Pin and 8 Pin, as well as between Florence and New York City. While 15 of 20 participants found Florence the more difficult city to virtually navigate through, the split between the perceptions of difficulty for the 4 Pin vs. 8 Pin route were even; 12 stated that the 4 Pin route was more difficult compared to 8 stating that the 8 Pin route was more difficult. Such findings in a group of young healthy adults likely speaks to the need to tailor and customize the perceived difficulty of the executive task to the individual, when utilized in a concurrent exercise-executive challenge, in addition to customizing the FITT principles of the exercise.

Previous videogame experience may have impacted performance based on sex differences, as only two of the ten female participants reported being videogame players, while five of the ten male participants reported being videogame players. Additionally, the types of games and gaming systems varied greatly among participants, from computer use, to commercially available console units, to videogame play on a phone or tablet. It has been suggested that those who play videogames tend to perform better than non-videogame players on tasks of executive function (Huang et al., 2017). It has also been suggested that those who use computer and console games are more likely to show improvements to metrics of executive function than those who play on a phone or tablet, due to the differing natures of the games; those who play on a computer or console are more likely to participate in action oriented games and are also more likely to engage in social interaction with fellow game players through online gaming platforms (Huang et al., 2017). Therefore, future work aiming to examine videogame play in relation to performance on virtual navigation tasks may need to consider and categorize videogame play in a more complex manner.

A secondary aim of this research was to examine individual performance on different executive tasks considered important for navigation, and examine relations between executive task performance and navigation performance. These participants were quite variable in their performance between the different executive domains; there did not seem to be a relation between an individual's performances on the different executive tasks. Ranking high within one task did not mean that they would rank high within another task. The exception was participant 17 who had a low executive task sum score, indicating that they ranked higher than most of the other participants in this study. In fact, as seen in Table 3.3, this individual ranked within the top 5 of 20 participants on four out of the five tasks; the exception being the Corsi block task where they ranked 13th. While sex differences were not examined for in this study with respect to performance on the executive tasks, previous research has demonstrated that males tend to outperform females on tasks requiring of visuospatial ability (Lövdén et al., 2007; Münzer et al, 2012). Furthermore, Münzer et al. (2012) demonstrated that an individual's visuospatial working memory capacity was predictive of their ability to learn the configural spatial layout of an environment. This relationship was not found in this study, although the tasks used and how performance scores were compared to each other are different amongst the studies. What was interesting was that the relationship between the performance rank on the Corsi block task to the sum navigation performance error was approaching significance, suggesting that performance on the Corsi block task may predict performance on this specific virtual navigation task. Knowing these relationships may help researchers and clinicians screen for virtual navigation abilities, an may help to guide a starting difficulty level for the virutal navigation task.

Based on participant feedback, this study found that the most important factor influencing participant's performance, as well as their preference for routes, was the ability to immediately locate the next target pin location. Participants preferred it when the next pin marker in the series became visible from their current pin location, or that it become visible relatively quickly after moving past the current pin the individual was currently at. This was common feedback from participants, stated both verbally while performing the task itself, and also in the written feedback that participants gave with respect to the different navigation task conditions.

3.7 Conclusions

This study did not find differences in performance on a virtual navigation task based on sex, route layout (grid vs. non-grid), or route length (4 pin vs. 8 pin). While these findings are contradictory to other scientific literature, the lack of performance differences based on these factors may indicate that this virtual navigation task design may be a good navigation task to couple with aerobic exercise. This task design may be relatively equally challenging for both male and female participants who are young healthy adults. Future work aiming to examine dual-task trade-offs in older healthy adults or patient populations using a similar coupling paradigm of aerobic cycling and virtual navigation should also aim to examine performance differences based on factors of sex, route layout and route length.

Chapter 4: Study 3

Dual-Task Trade-Offs of Coupling Aerobic Cycling with Virtual Navigation

4.1 Introduction

Finding novel ways to improve executive function has become a prominent area of research within the past decade. Early research focused on improving executive function by simply training executive function. However, aerobic exercise has emerged within the literature as another means for promoting improvements to executive function and brain health (Bamidis et al., 2014; Bherer, 2015;). Even more recently, research has begun to focus on the possibility of combining exercise and executive training in a concurrent manner, with the promise of an additive effect to executive outcomes. This concurrent combination of exercise and executive training is commonly referred to as 'exergaming', and can be implemented through the use of interactive videogame systems, such as Dance Dance Revolution® and Nintendo Wii™, or by connecting a computer system to traditional exercise equipment enabling interaction with a secondary task while exercising (Anderson-Hanley et al., 2012; Bamidis et al., 2015; Ogawa et al., 2016; O'Leary et al., 2011). O'Leary et al. (2011) examined behavioural and neurophysiological changes to inhibitory control in young healthy adults after partaking in videogame play, aerobic exercise (treadmill walking) and exergaming. They found that while there was no significant difference in heart rate between the treadmill walking and the exergaming task, treadmill walking was the only task to influence cortical activity associated with the modified Flanker task as assessed using the P3 event related potential; neither videogame play alone nor exergaming led to significant improvements (O'Leary et al., 2011). Eggenberger et al.

(2015) examined two different concurrent aerobic-executive interventions compared to a solely aerobic intervention in healthy older adults (aged > 70 years). Participants were randomized into one of three groups: treadmill walking (no secondary executive task), treadmill walking with simultaneous performance of a computerized memory task, and a virtual reality dancing program with stepping sequences. Participants also performed additional resistance and balance training, with that training being the same for all three groups (Eggenberger et al., 2015). They found that there was a trend towards a significant improvement in executive function for those in the concurrent exercise-executive training compared to those who solely performed aerobic walking on the treadmill. They also found a trend towards a preference of the dual-task training paradigms over the exercise only paradigm (Eggenberger et al., 2015). However, what was not reported are the potential differences in the physiological requirements to perform the different modes of exercise.

It was previously proposed that virtual navigation may be a pragmatic executive task to concurrently couple with aerobic exercise, specifically aerobic cycling. Navigation requires the simultaneous use of numerous executive domains, such as attention, working memory and visuospatial working memory, decision making, planning and inhibition (Bates & Wolbers, 2014). The requirement for simultaneous use of multiple executive domains may increase the likelihood of improvement to multiple domains of executive function, to broader cognitive functions, and to activities of daily living (Moffat, 2009). Navigation also has a natural coupling with rhythmic locomotor activity, such as walking, running and cycling, and therefore also presents the possibility that a concurrent cycling-virtual navigation paradigm has the propensity to a) promote improvements to executive function that will transfer to activities of daily living, and b) may decrease dual-task interference arising as individuals have likely amassed mass practice of simultaneous rhythmic movement with navigation.

The concern of concurrently coupling aerobic exercise with an executive task is the inevitability of a dual-task trade-off. Dual-task studies examining executive task performance while walking demonstrate alterations to gait speed and step length variability when performing dual-task walking when compared to walking alone (Nagamatsu et al., 2011). Studies examining the potential for concurrent aerobic and executive training have solely focused on the executive outcomes of the training regime with little to no consideration about the impact to the aerobic training portion. While aerobic exercise has shown to be a robust means for improving cognition and executive function, one of the primary roles (if not *the* primary role) of aerobic exercise is to maintain or improve aerobic capacity (Wilson et al., 2016). What is currently unknown is the likely alterations to the parameters of the movement required of the exercise, as well as the heart rate of individuals performing dual-task training.

Dual-task activities require executive resources, which are limited in capacity, and dividing these resources between two or more tasks leads to a decrement in task performance, particularly when one or more of the tasks places a high demand on executive resources (Nagamatsu et al., 2011; Plummer & Eskes, 2015). Aging reduces one's capacity for successful dual-tasking, as do neurological disorders such as stroke, due to an increase in executive demand required to maintain control over the motor performance aspect of the task or tasks required of the paradigm (Nagamatsu et al., 2011; Plummer & Eskes, 2015). Therefore, for those with neurological impairments, dual-task walking is becoming an important focus of neurorehabilitation (Plummer & Eskes, 2015).

The first study in this thesis found that individuals decreased their cycling cadence while simultaneously performing virtual navigation with cycling compared to cycling alone. Changes to cadence were additionally influenced by the goal of the virtual navigation task itself. Participants performed two separate virtual navigation tasks: during the navigation condition individuals were asked to make their way from an origin to a destination, and then return to the point of origin, while in the explore condition, individuals were given free rein to move about the virtual environment and explore the area at their leisure. Cadence was slower when exploring as compared to the goal directed behaviour of navigating to a specified point within the environment. The second study of this thesis explored factors of the goal directed navigation task with respect to performance outcomes and likability on the part of the individual. The factors examined were the length of the route (and therefore the number of turns to remember), as well as the layout of the environment (grid like vs. no discernable pattern). The sample of young healthy adults preferred routes that had wider roads compared to narrow streets and alleys, and also preferred routes where the pin markers they were asked to find were closer together, such that the pin N became visible relatively quickly after passing through pin N-1.

Therefore, based on the findings from the previous studies, it is likely that performance metrics of the aerobic exercise and the virtual navigation task will be influenced by the nature of the dual-task paradigm that is implemented. What is unknown from the previous studies is how performance of both the cycling and the virtual navigation tasks differ from single task to dual task performance. Does the virtual navigation task that has been designed and implemented as a solo executive task transfer well to a dual-task paradigm? Does this particular virtual navigation task result in differences to cycling cadence and cadence variability that would then result in participants not receiving the aerobic benefits of exercise? Lastly, what are participant's perceptions of task difficulty and task enjoyment?

Therefore, the primary objective of this study was to examine the specific dual-task trade-off effects of concurrently combining aerobic cycling with virtual navigation. The virtual navigation task used was based on the protocol developed in the previous studies of this thesis using a recumbent cycle ergometer and joystick control (for direction) to control motion about a virtual cityscape. It was hypothesized that young healthy adults would show a reduction in cycling cadence and power output, and an increase in cadence variability when asked to simultaneously cycle and navigate when compared to cycling alone. The secondary objective was to examine measures of perceived exertion associated with the dual-task paradigm, as well as the perceived executive demands of the tasks. It was hypothesized that young healthy adults would not experience an increase in perceived exertion when coupling the exercise and the executive task.

4.2 Methods

Participants

Seventeen healthy young adults (7 females, 10 males) participated in the study (aged 18 – 29, mean (± sd) age = 22.2 ± 3.9 years, height = 168.2 ± 8.4 cm, and weight = 65.3 ± 15.1 kg. All participants completed the Get Active Questionnaire (GAQ), provided self-reports of educational background, exercise participation level, video game experience and navigational experience. Participants reported no neurological or musculoskeletal conditions that would affect their ability to perform the exercise protocol required of the experiment, including being non-smoking, and not pregnant, no known cardiovascular or respiratory conditions that would be negatively impacted by exercise, and no uncontrolled medical conditions. Participants also had normal or corrected to normal vision with no reported visual impairments (e.g. colour blindness), and had no known symptoms of cyber-sickness associated with computer use or videogame play in order to perform the computerized virtual navigation task. This study received clearance from the Office of Research Ethics at the University of Waterloo, and all participants provided written consent prior to study participation. Details of participant demographics can be found in Table 4.1.

Participant Demographic Information

Category	Female	Male	Cohort Combined
Age (years)	21 ± 2.9 (18 – 26)	23 ± 4.4 (18 – 29)	22.2 ± 3.9 (18 – 29)
Height (cm)	160.1 ± 3.9 (153 – 165)	173.9 ± 5.3 (168 – 183)	168.2 ± 8.4 (153 – 183)
Weight (kg)	55.4 ± 9.6 (42.4 – 72.8)	72.3 ± 14.5 (54.8 – 105.5)	65.3 ± 15.1 (42.4 – 105.5)
VO_{2peak} (mL/kg/min)	41.5 ± 7.2 (29.5 – 52.4)	46.1 ± 9 (33.7 – 55)	44.2 ± 8.4 (29.5 – 55)
Target Heart Rate (bpm)	123.7 ± 6.7 (115 – 133)	128.7 ± 8.1 (115 – 143)	127.7 ± 7.8 (115 – 143)
Preferred Cadence (RPM)	60.7 ± 9.8 (50 – 80)	63.5 ± 11.6 (50 – 90)	62.4 ± 10.6 (50 – 90)

Table 4.1: Participant demographic information by sex and as a combined cohort. Values are means ± standard deviation. Values that are in brackets are the range of values within the category.

Participant Demographic Questionnaire

Participants completed a demographic questionnaire to attain information regarding their educational background and field of study. They were also asked to identify their participation in exercise as well as exercise preferences. Participants then answered questions regarding their videogame play habits, and how often they navigate as a driver of a vehicle, passenger in a vehicle or driver of a bicycle.

Participants then completed 12 visual analog scales to attain their perception of their videogame playing habits as well as their perception of their navigation ability. Perceptions for questions related to navigation experience were combined to create a composite score for Overall Navigation Ability, and perceptions for videogame play habits were combined to create a composite score for Overall Videogame Play Ability. Please see Appendix F for the demographics questionnaire. A summary of the responses from the demographics questionnaire can be found in Table 4.2 below.

Participant Questionnaire Data

Category	Female	Male
Handedness: Right/Left	7/0	7/3
Program: Kinesiology / Other Science	5/2	8/2
Level of Study: Undergraduate / Graduate	5/2	5/5
Self Reported Exercise Hours / Week:	6.3 ± 4.3	6.2 ± 4.7
Hours per week driving:	1.1 ± 2	2.6 ± 2.8
Hours per week as a passenger:	0.4 ± 0.8	1.3 ± 1.6
Hours per week on Public Transit:	3.1 ± 2.4	1.1 ± 1.3
Self Reported Video Game Player: Yes / No	2/5	8/2
Video Game Preference: Immersive / Non-Immersive	1/1	6/2
Hours per day playing video games:	0.3 ± 0.5	1.3 ± 1.3

Table 4.2: Summary of the findings from the participant demographic questionnaire by sex. Values are means ± standard deviation, or a count between the two categories listed.

Psychometric Questionnaires

Upon arrival at the lab, participants rated their overall level of fatigue using the Rating of Fatigue (ROF) scale (Appendix B) (Micklewright et al., 2017). This measure was taken again upon completion of the task. At the end of each session for sessions 1-3, participants completed the NASA Task Load Index (NASA-TLX) (Appendix C). The NASA-TLX is a questionnaire that examines mental workload in the following six domains: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration (Hart & Staveland, 1988). These domains are provided individually, along with a descriptive prompt for each domain. Underneath each prompt is a 20 point Likert scale which ranges from "very low" to "very high", with the exception of the Performance domain, which ranges from "perfect" to "failure" (Hart & Staveland, 1988). Values can be examined for each domain individually, or may be summed to provide one overall task load value. Higher values of individual domain scores and total scores indicate greater stresses to mental workload.

A Visual Analog Scale (VAS) was also designed and administered to participants after each navigation task that was performed. Participants were asked to rate how difficult they found the virtual navigation task from "no difficulty" (score of zero) to "extremely difficult" (score of 10). Participants were also given the opportunity to provide feedback on their overall impressions of the task, and the strategies that they used to complete the task.

Overview of General Experimental Set-Up

Participants attended the lab on four separate occasions. The first session was the intake session which consisted of: screening, questionnaires, familiarization with Google Earth and a maximal graded exercise test. The three experimental sessions were: 1) a navigation only (NAV) session, 2) an aerobic cycling exercise only (EXE) session and, 3) a concurrent exercise-navigation (DUAL) session. Experimental sessions 1-3 were scheduled to all occur in the morning or the afternoon within an individual, with 1 – 11 days between sessions.

1) Intake Session

In the intake session, participants completed the demographic questionnaire to attain information regarding their educational background, videogame play experience, and navigation experience. Participants were familiarized with the virtual navigation task using the Google Earth platform. A practice route in the city of Toronto, Canada, was used to familiarize participants with the virtual graphics, the program controls, and the instructions for the virtual navigation task. Finally, participants partook in a maximal oxygen uptake (VO_{2max}) testing procedure in order to determine individual VO_{2peak} values to set the appropriate exercise intensity for later experimental sessions.

Experimental sessions 1-3 were block randomized amongst participants between the cycling exercise only, virtual navigation only, and concurrently coupled exercise-executive task conditions. To remove expectancy effects from biasing the results, each participant was informed of their session order prior to the initiation of the experimental sessions.

Experimental Sessions

1) *Exercise Only Session*

For the exercise (EXE) session, participants were asked to cycle on a recumbent cycle ergometer for 30 minutes. Prior to exercise, participants were asked to sit quietly for 5 minutes in order to attain a resting heart rate. Participants were given a 5-minute warm-up period in order to reach their target heart rate which was set to 50-60% of their VO_2 reserve as determined from the maximal graded exercise test. Participants continued to exercise for an additional 20 minutes before beginning a 5-minute cool down. Rate of perceived exertion (RPE) was recorded every 5 minutes throughout the exercise session using the 10-point Borg RPE scale (Appendix A).

2) *Navigation Only Session*

The virtual navigation task was performed using the free download platform of Google Earth in the 3D rendered version of street view, providing a first person view of movement through the virtual environment. In the intake session, and in the navigation only session, movement through the environment was performed using a computer keyboard: up and down arrow keys to move forward and backward, respectively, while left and right arrow keys to make leftward and rightward turns, respectively.

At the beginning of the navigation only session and the dual-task session, participants were asked to sit quietly to attain a resting heart rate. Participants were given a short practice navigation task in order to re-familiarize them with the controls, and the instructions of the task. The same route within the city of Toronto that was used in the intake session was used as the practice route. The practice route within Toronto had a total of three pins, while the experimental route in London, England, had a total of seven pins. For the practice route (Toronto) and the experimental route (London, England), participants were given virtual pin as a start point. All pins were labelled with an associated numerical value. Participants were placed at Pin 1 and in the direction necessary to find Pin 2 (i.e. Pin 2 was not behind them). Participants were instructed to move from Pin 1 to Pin2, and then make their way back to Pin 1. From there, participants were asked to turn around, and then proceed to move from Pin 1, to Pin 2, and then to Pin 3, and again return to Pin 1, connecting through Pin 2. This process was repeated until 1) the participant successfully connected all 7 pins in the route and had returned to Pin 1 or 2) the 20-minute time limit on the task had been reached. Details of the routes within Google Earth can be found in Table 4.3.

Google Earth Route Information

Route	Total Route Distance (m)	# Left Turns	# Right Turns	Total # Turns	Mean Distance (m) between Pins	SD Distance (m) between Pins
Practice Route Toronto, Ontario	1.980	1	1	2	318	101.8
Experimental Route London, England	11.834	5	3	8	274.2	64.2

Table 4.3: Summary of the Google Earth route information. Total route distance is the total distance the participant would travel if participants completed the task along an ideal route. The number of turns are depicted as the number of turns one would take when travelling from Pin 1 to Pin 7 a single time, and ceasing the task at Pin 7.

3) Concurrent Exercise & Virtual Navigation

This session combined the above interventions. Again, participants sat on the bike for 5 minutes in order to record a resting heart rate. They were then given a 5-minute warm-up period to enable their heart rate to achieve a corresponding 50-60% of their VO_2 reserve. Upon the start of the exercise period, participants were placed in Google Earth and asked to perform the same navigation task outlined above. The navigation route for the navigation only and the exercise-executive intervention was the same route. During the DUAL session, a joystick was connected to the computer and held in the participant's preferred hand, and was used in order to make left and right turns. The recumbent cycle ergometer was fitted with a magnetic sensor so that the forward pedalling motion of the participant elicited the forward motion in Google Earth. The forward motion in Google Earth is a fixed rate, and therefore the speed of movement in the virtual environment was independent of cycling cadence. Again, RPE was measured every 5 minutes throughout the exercise.

Figure 4.1: A) The experimental route from London, England used in the experiment from an aerial view; **B**) First person view of the virtual navigation task in the 3D rendered setting of Google Earth. The white box has been added to highlight where Pin 2 is, as it can be seen in the distance from Pin 1.

VO_2 Max Testing

To perform VO_{2max} testing, the Vmax® Encore Breath-by-Breath System (Care Fusion, SanDiego, CA) was used in conjunction with a Burdick EK10 electrocardiograph and an upright electronic cycle ergometer: VIAsprint® 200P Cycle Ergometer (Ergoline GmbH, Bitz, Germany). In order to attain heart rate, the CM5 electrode placement was used with a single electrode in each of the following locations: manubrium, 5th rib on the right, and 5th rib on the left, both inferior and lateral to the nipple line. For female participants, this was the bottom and lateral edge of a sports bra. Skin sites were cleaned using NuPrep abrasive gel, and then again using alcohol swabs to remove any remnants of the gel. Participants were then assisted onto the cycle ergometer and the seat height was adjusted so that there was a slight bend in the knee when the leg was at full extension. Participants were then fitted with the headpiece and flow sensor to collect ventilation values. Participants sat quietly on the bike for 2 minutes to attain resting values, and were then given a 2 minute warm up at a workload of 50-75 Watts, at a cadence of their choice. This cadence was recorded for use during future experimental sessions. There was then a 1-minute rest period to ensure the participant was comfortable and to ensure all equipment was working properly. Then participants began the VO_{2max} testing procedure. Work rate started at 25 Watts, and increased in a step-wise manner by 25 Watts every 60 seconds. Participants were asked to maintain the cadence that they cycled at during the warm-up. Test cessation criteria were the following: a) volitional cessation by the participant, b) cadence drops 10 RPM below the preferred cadence for a period of 10 seconds or longer, c) respiratory exchange ration ≥ 1.1, d) heart rate fails to increase with continued increase in work rate or e) signs / symptoms experienced by the participant indicating cessation of the test.

The Vmax Vision SensorMedics Inc. software provides continuous analysis of a multitude of variables including: oxygen consumption (VO_2), heart rate (HR) and the respiratory exchange ratio (RER). These variables are displayed in real time during testing, and are stored for later processing and analysis. Additionally, rate of perceived exertion (RPE) using the 10-point Borg Scale (Appendix A) was taken at the end of each work rate. In offline analysis, VO_2, HR and RER were averaged into 20 second bins. To determine if VO_{2peak} was achieved, common criteria include: VO_2 increase of 2.1 mL/kg/min or less for an increase in workload, RER > 1.1, RPE peak > 9 and HR > 90% age predicted max heart rate (220-age). In order to achieve a true VO_{2peak}, at least 2 of these criteria must be met during the test.

4.3 Instrumentation & Data Acquisition

The recumbent cycle ergometer (Technogym® 700, Technogym, USA Corp.) used for the exercise only and exercise-navigation tasks was equipped with a voltage box that created a voltage pulse with every revolution of the wheel, enabling the continuous collection of cadence data. Participants wore a heart rate monitor that to record heart rate over the entirety of the session in order to examine how heart rate changed as a function of changes to cadence and task demand (i.e. single or dual-task cycling). This was done using the Bittium accelerometer (Bittium Faros, Bittium Biosignals Oy/Mega Electronics, Kuopio, Finland) that recorded heart rate continuously throughout each task to examine heart rate changes as a function of changes to cadence. Electrocardiography (ECG) was collected using self-adhesive electrodes from three electrode sites: 5 cm to the left and to the right of the inferior portion of the manubrium, and on the 5-6th rib lateral to the nipple line on the left hand side of the participant. Skin sites were first abraded with NuPrep skin preparation gel and then cleaned with rubbing alcohol. The researcher also monitored heart rate continuously throughout exercise with a Polar Heart Rate Monitor (Polar Electro Oy, Kempele, Finland).

The Google Earth program allows users to record the global positions coordinates of their navigation performance, and to save this as a keyhole markup language (KML) file. From this KML file, one is able to attain latitude and longitude coordinates, recorded twice per second. These values were then converted into a distance travelled in meters to attain an overall distance travelled.

With a custom built LabView program, information regarding keyboard or joystick use was collected. This enabled the analysis of when turns were made, when individuals were moving forward, moving backward or if they had times where they were not moving at all but rather were looking around, referred to as 'dwell time'.

4.4 Data Analysis

Data was analyzed using a custom built LabView program (National Instruments, Austin TX, USA). Revolutions per minute was determined by the cycle pulse box that was embedded next to the fly wheel of the bike. Power output was determined over the course of the exercise from the RPM data and the resistance level setting on the bike. Cadence means were calculated as individual cycle time for each revolution, and then taking the reciprocal to achieve a value in revolutions per minute. These values were then averaged across the 20-minute exercise protocol to examine cadence over time of the exercise. Standard deviation was then calculated from this average. Cadence variability was calculated as the average standard deviation of cycling cadence in RPM across the individuals. Heart rate data was run through a dual-pass, bandpass, second order

Butterworth filter, with low and high frequency cut-offs of 500 and 1 Hz, respectively. Heart rate average and standard deviation were then calculated for the 20 minutes of exercise when participants were to be at 50-60% of their VO_2 reserve.

The coordinate data from Google Earth was processed in LabView, using a calculation to determine difference in distance from one latitude & longitude sample to the next sample (see equation from Study 2 on page 84). The joystick data was also processed in LabView in order to determine time points when turns were made. This information was used to examine durations of time spent turning or making adjustments to heading as a function of total travel time. The overall distance that participants travelled in the Google Earth environment was calculated for both the navigation only and concurrent exercise-executive challenge task conditions. Additional measures included the total time spent moving forward within the environment, the total dwell time (i.e. time not moving forward, rather remaining in one place to look around), as well as the total turn time. Total turn time includes a summation of turns or adjustments that occurred while moving forward and while not moving forward.

4.5 Statistical Analysis

One-way repeated measure ANOVAs were used to examine the differences in performance measures between single and dual-task conditions. These comparisons include RPM mean, RPM variability and heart rate means. Additional one-way repeated measure ANOVA comparisons were made to compare navigation performance between the navigation only condition and the dual-task condition. Finally, one-way repeated measure ANOVAs were used to compare possible differences in perceived difficulty of tasks, as well as the domains of task demand as assessed within the NASA Task Load Index. A Tukey's

Post Hoc test was used for post hoc analysis where necessary. The significance level was set to $\alpha = 0.05$.

4.6 Results

Physiological and Behavioural Metrics of the Exercise

Cycling cadence means over the 20-minute aerobic exercise portion of the tasks were 64.59 ± 6.53 RPM for the cycle only task and 58.18 ± 9.06 RPM for the dual-task conditions. There was a significant effect of task, such that mean cadence in the cycle only condition was higher than mean cadence in the dual-task condition ($F_{1,30} = 543.6$($p = 0.027$)). Cadence variability, measured as the average standard deviation values within each of the tasks, were 2.64 RPM for the cycle only task and 8.55 RPM for the dual-task conditions. Cadence variability was not found to be statistically significant ($F_{1,30} = 4.06$ ($p = 0.29$)). Average power output (Watts) values were 86.85 ± 22.67 and 78.32 ± 27.68 for the cycle only and dual-task conditions respectively, and were not found to be statistically significant ($F_{1,30} = 8.48$ ($p = 0.21$)). The mean variability averaged across participants with respect to power output (Watts) measured as a value of average standard deviation were 5.57 and 11.63 for the cycle only and dual-task conditions respectively, and were also not statistically significant ($F_{1,30} = 0.20$ ($p = 0.73$)).

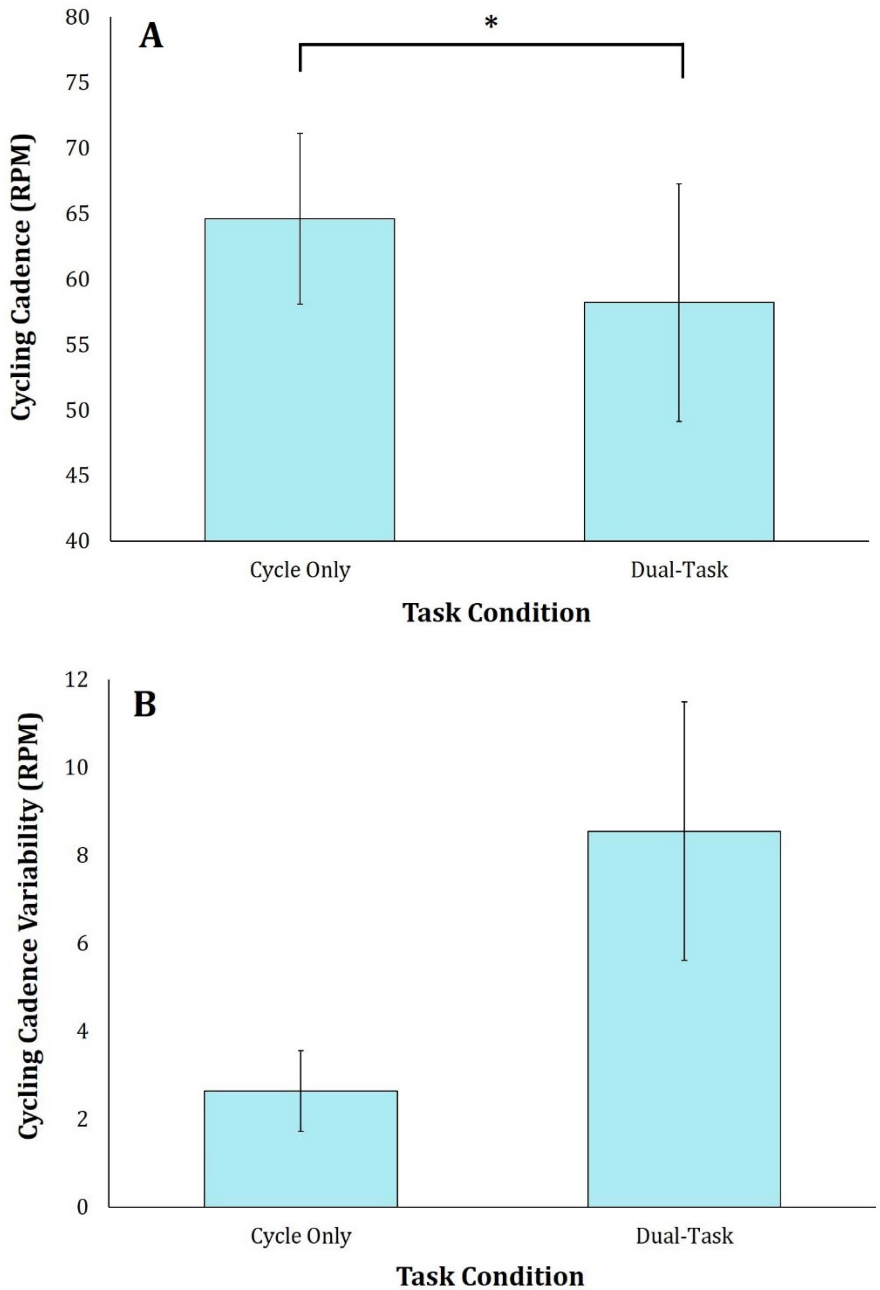


Figure 4.2: A) Mean (± sd) cycling cadence (RPM) during the Cycling Only and Dual-Task conditions; **B**) Average standard deviation values of mean cycling cadence (RPM) during the Cycling Only and Dual-Task condition; $^*p < 0.05$.

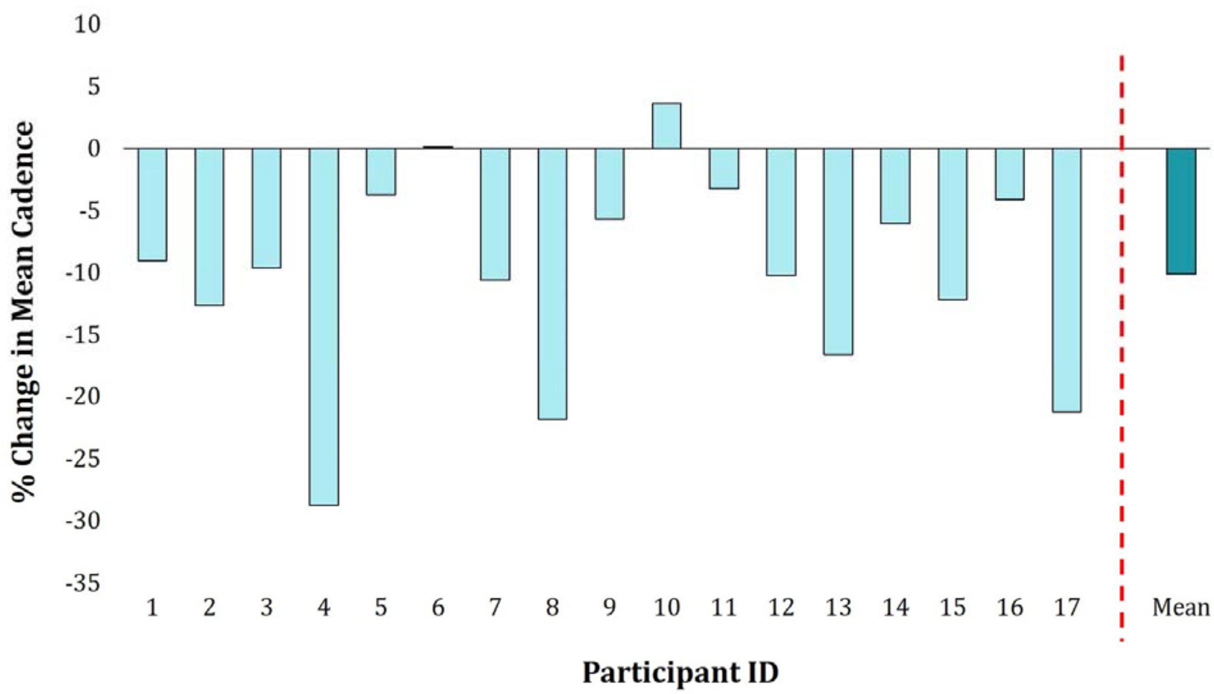


Figure 4.3: Dual-task cost as a function of change in cycling cadence when performing the dual-task paradigm in comparison to cycling alone. There is considerable variability amongst individual participants; Mean is the average dual-task cost of across the group of participants.

The average heart rate values over the 20 minutes of the task interventions were 72.37 ± 10.93 bpm, 128.53 ± 12.93 bpm and 117.57 ± 15.79 bpm for the navigation only, cycle only and dual-task conditions respectively. There was a main effect of task condition on heart rate ($F_{2,45} = 29.77$ ($p = 0.033$)), and the post hoc testing revealed that heart rate during navigation was significantly lower than heart rate during the two exercise tasks. Conversely, there was no significant difference in heart rate between the cycle only and dual-task conditions. Resting heart rate was measured for a 5-minute span at the beginning of each session, and there was no significant difference in resting heart rate between session order ($F_{2,44} = 0.17$ ($p = 0.85$)).

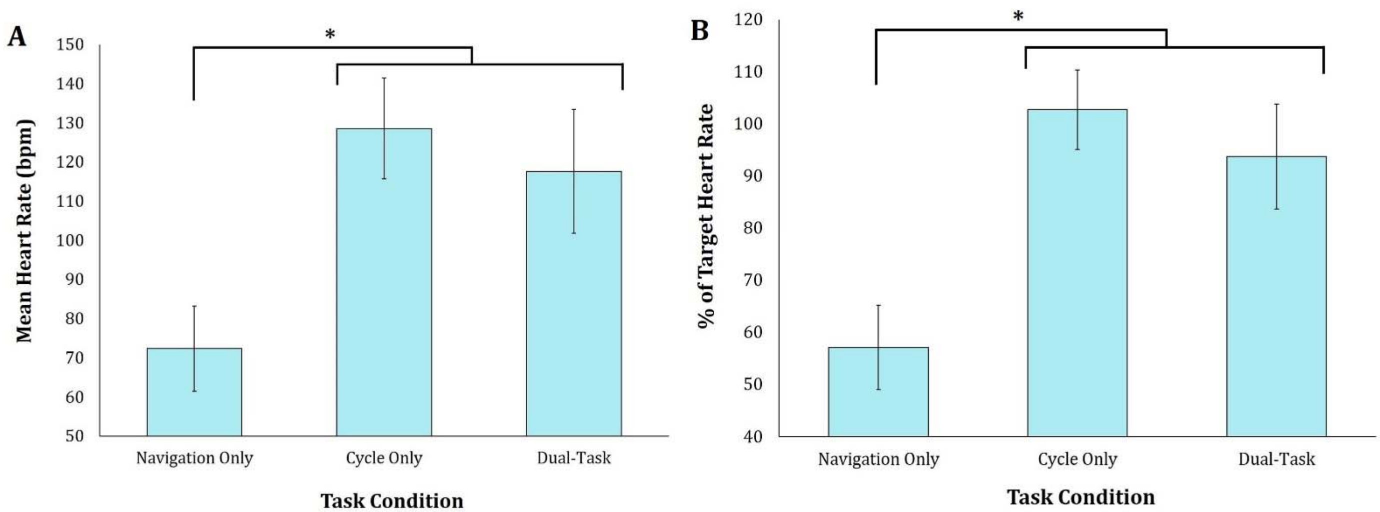


Figure 4.4: A) Mean (± sd) heart rate values over the 20 minutes of task performance of the three task conditions (expressed in absolute values); **B**) Mean (± sd) heart rate values over the 20 minutes of task performance of the three task conditions (expressed in values relative to the target heart rate as determined from the $VO2_{max}$ test procedure); *p <0.05.

A one way repeated measures ANOVA on RPE data revealed that there was no effect of task on the average rate of perceived exertion between the cycling only and the dual-task conditions ($F_{1,30} = 2.76$ ($p = 0.34$)). Additionally, while not statistically significant, RPE for the dual-task condition was lower than the RPE for the cycling only condition across the first 3 time points. The average RPE at time point 4 (the cessation of exercise), is the same value for both task conditions. These findings can be seen in Figure 4.5.

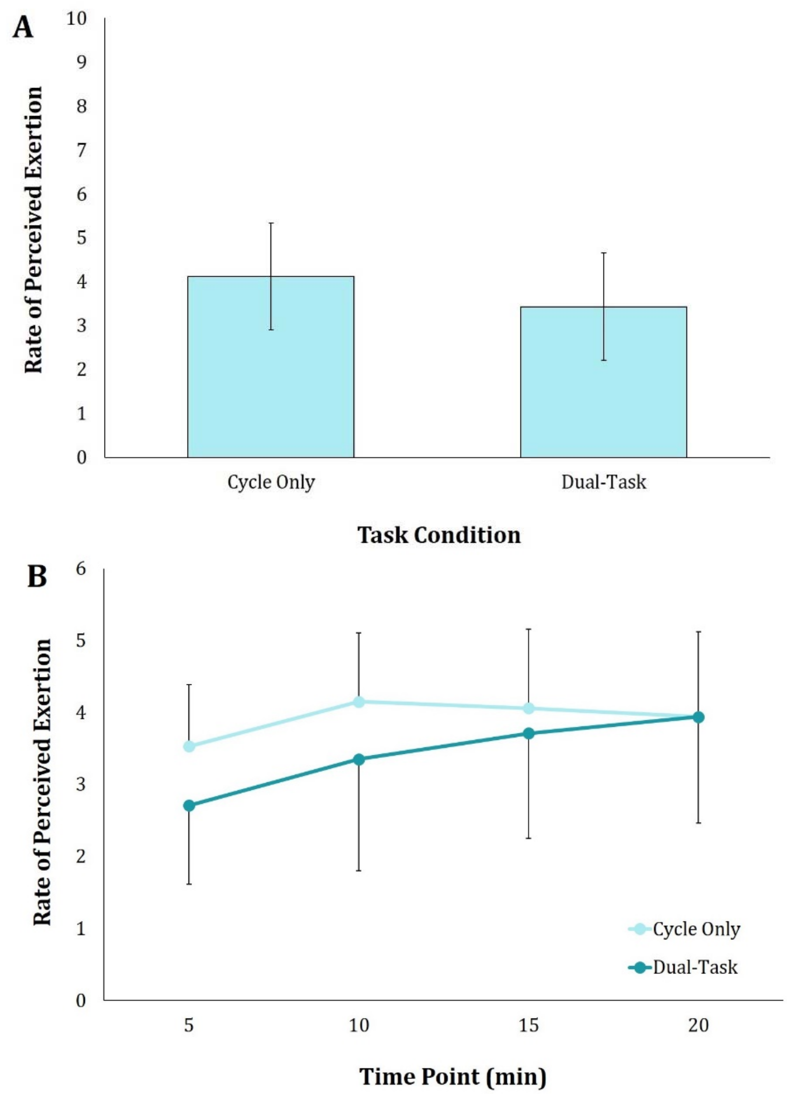


Figure 4.5: A) Average (± sd) RPE for the cycling only and dual-task conditions; **B**) Average (± sd) RPE at each of the four time points of measurement throughout the exercise tasks.

Navigation Task Performance Data

The overall distance that participants travelled in the Google Earth environment was calculated for both the navigation only and concurrent exercise-executive challenge task conditions. Additional measures included the total time spent moving forward within the environment, the total dwell time (i.e. time not moving forward, rather remaining in one place to look around), as well as the total turn time. Total turn time includes a summation of turns or adjustments that occurred while moving forward and while not moving forward.

With respect to the effects of task, (navigation only vs. dual-task), there was no main effect for total distance covered ($F_{1,28} = 4.72$ ($p = 0.27$)) with the mean distance covered in the navigation only task of 11.01 ± 0.8 km and 11.01 ± 1.0 km for the dual-task condition. There was no main effect for time moving forward ($F_{1,28} = 1.74$ ($p = 0.41$)) with mean forward motion times of 18 ± 1.2 min and 17.4 ± 1.2 min for the navigation only and dual-task conditions respectively. There was also no main effect for dwell time ($F_{1,28} = 0.08$ ($p = 0.82$)), with dwell times of 1.8 ± 1.4 min and 2.5 ± 1.3 min for the navigation and dual-task only conditions, respectively. There was a main effect of task on total turn time ($F_{1,28} = 166.42$ ($p = 0.049$)), such that there was greater turn time for the dual-task condition as compared to the navigation only condition as revealed through post hoc testing ($p = 0.021$). Mean turn times were 3.38 ± 0.36 min and 3.41 ± 0.45 min for the navigation only and dual-task conditions respectively.

With respect to session order, there was a main effect for distance travelled ($F_{1,28} = 208.11$ ($p = 0.04$)) in that, regardless of order of task performance (navigation only or dual-task) total distance travelled on the participant's second exposure to the route was longer ($p = 0.021$). The average distance (km) travelled in the first session was 10.6 ± 0.94 km while the average distance travelled in the second session was 11.5 ± 0.52 km. There was also a main effect of session order on the total time spent travelling in a forward motion ($F_{1,28} = 305.48$ ($p = 0.036$)). Post hoc testing revealed that participants spent more time travelling forward in their second exposure to the task, as mean forward travel times were

17.2 ± 1.1 minutes and 18.2 ± 1.1 minutes for the first session requiring virtual navigation vs. the second virtual navigation session, respectively. There were no main effects for session order with respect to both dwell time ($F_{1,28}$ = 5.26 (p = 0.26)) and total turn time ($F_{1,28}$ = 0.0 (p = 0.97)).

Due to the design of the experiment, with the navigation task being cut off at 20 minutes, and with Google Earth only allowing a constant speed of movement (no way to speed up or slow down; just moving/not moving) differences in task performance may not be visible by means of distance measurements due to the issue of a ceiling effect. Of the 17 participants in the study, two successfully completed the virtual navigation task, both on their second exposure to the route. Therefore, performance on the navigation task was additionally analyzed with respect to a navigation score of performance. Reaching a pin in the correct order of performance of the task was assigned a numerical value. If participants reached the pin they were assigned that value. If participants ended between pins, there were given half points. This scoring system can be seen in Appendix G. The maximal score a participant could receive was 42 points. One-way repeated measures ANOVAs were performed in order to examine main effects of task and session order, as well as a possible interaction effect. There was no main effect of task condition (navigation only vs. dual-task) on performance score ($F_{1,29}$ = 0.10 (p = 0.81)) and no main effect of session order on performance score ($F_{1,29}$ = 0.21 (p = 0.73)). The mean (± sd) scores by task were 37.1 ± 4.3 and 36.7 ± 3.5 for the navigation and dual-task conditions respectively. The mean (± sd) scores by session order were 34.4 ± 3.6 and 39.4 ± 2.3 for sessions 1 and 2 respectively.

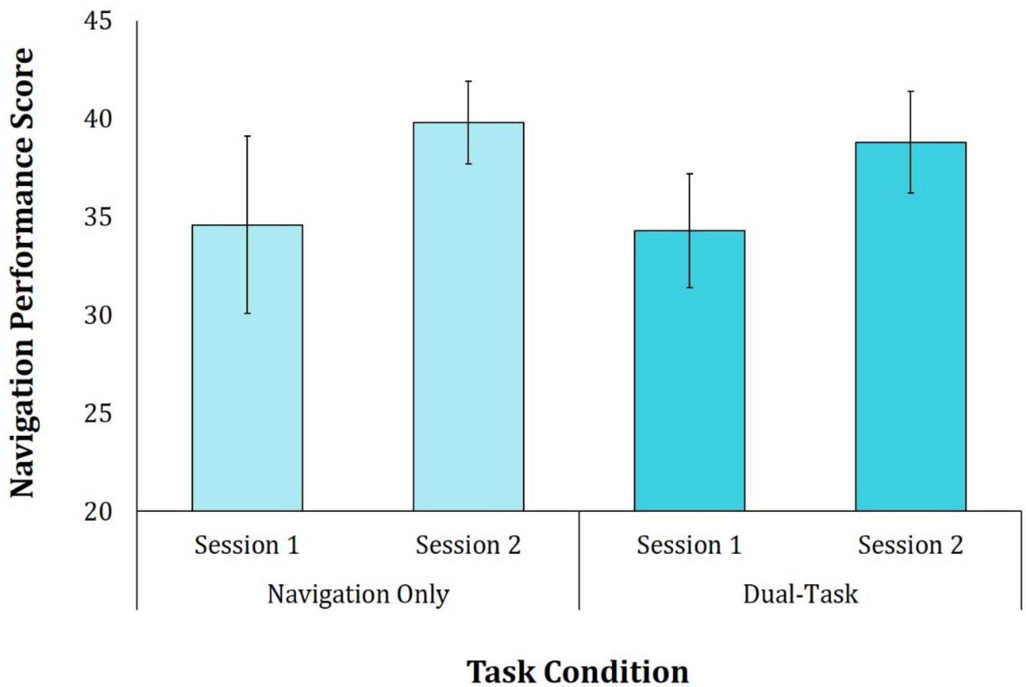


Figure 4.6: Average navigation performance scores by task (navigation only and the dual-task paradigm) as well as by order of session exposure to the navigation task (i.e. if participants were exposed to the navigation only task prior to the dual-task, or the dual-task prior to the navigation task).

Psychometric Data

The NASA Task Load Index values were examined within each domain, and as a total sum score across all six domains within the questionnaire. Within the Mental domain, the average (± sd) scores were 7.4 ± 5.4, 2.6 ± 2.1 and 9.8 ± 4.4 for the navigation, cycle only and dual-task conditions respectively. The main effect of task in the ANOVA approached significance at ($F_{2,45}$ = 13.45 (p = 0.069)), such that the mental demand of the cycling task was approaching a statistically significant reduction from the mental demands required for the navigation only and dual-task conditions. Within the Physical domain, the average scores were 1.4 ± 3.0, 10.4 ± 4.5, and 10.9 ± 3.5 for the navigation, cycle only, and dual-task conditions respectively. There was a statistically significant difference for Physical demand between the tasks ($F_{2,45}$ = 22.12 (p = 0.043)). Post hoc testing revealed that the physical demand for the navigation only task was significantly less that the physical demand of the two exercise tasks. Within the Temporal domain, the averages and standard deviations were 10.9 ± 6.0, 4.3 ± 3.3 and 11.2 ± 4.9 for the navigation, cycle only and dual-task conditions respectively. There was no statistically significant difference between the tasks ($F_{2,45}$ = 1.89 (p = 0.35)). Within the Performance domain, the averages and standard deviations were 7.7 ± 6.2, 4.9 ± 4.5 and 8.6 ± 5.2 for the navigation, cycle only and dual-task conditions respectively. Note that for the Performance domain, lower scores indicate a higher or better perceived performance of the task. The main effect in the ANOVA approached significance at ($F_{2,45}$ = 16.91 (p = 0.0558)), such that participants perceived their performance on the cycle only task to be significantly better than their performance on both the navigation only and dual-task conditions. Within the Effort domain, the average scores were 6.6 ± 4.9, 10.7 ± 4.0 and 11.5 ± 3.6 for the navigation, cycle only and dual-task conditions respectively, and there was no statistical significant difference between the tasks with respect to the effort that was required to perform the tasks ($F_{2,45}$ = 5.63 (p = 0.15)). Within the Frustration domain, the average scores were 4.5 ± 5.4, 1.6 ± 1.4 and 7.0 ± 5.6 for the navigation, cycle only and dual-task conditions respectively, and there was no statistical significant difference between the tasks with respect to the amount of frustration that participants perceived for the tasks ($F_{2,45}$ = 6.77 (p = 0.13)). Lastly, the Total NASA TLX scores were tabulated, such that higher values indicate higher overall mental and physical demands in order to complete the tasks. The average scores were 38.5 ± 21.3, 34.6 ± 12.0 and 59.1 ± 18.2 for the navigation, cycle only and dual-task conditions respectively, and reached a significant difference ($F_{2,45}$ = 40.08 (p = 0.024)). Post hoc testing revealed that there was no significant difference in total task demands between the navigation only and the cycle only tasks, while the total task demands for the dual-task was significantly higher than both of the navigation and cycle only tasks.

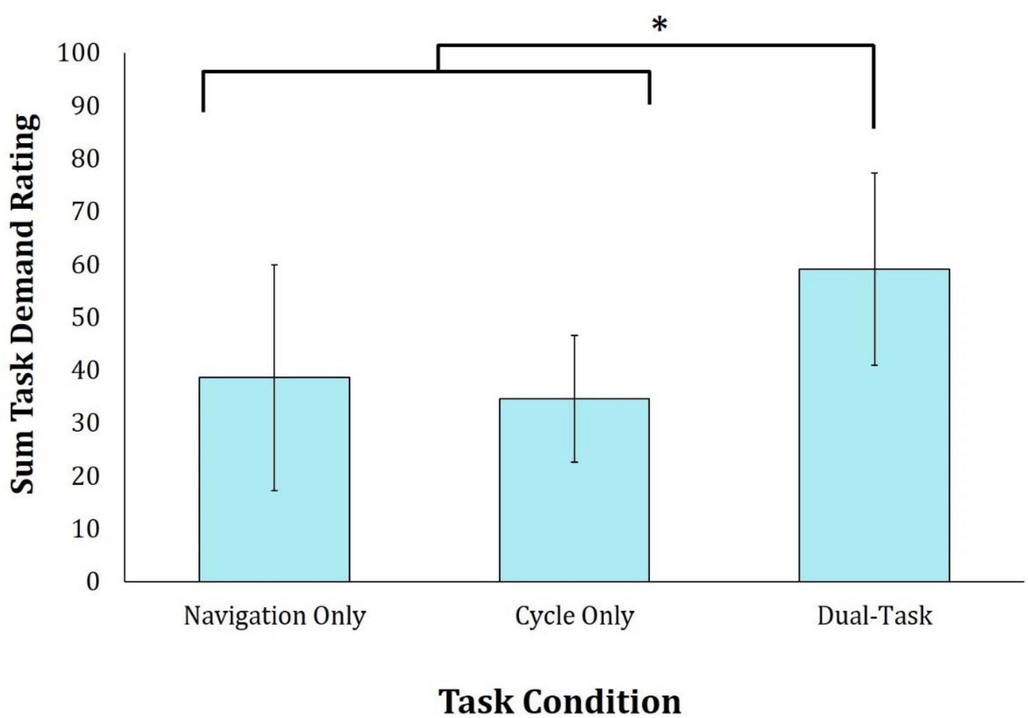


Figure 4.7: Average NASA TLX Sum Scores (a sum of the scores from each of the six domains within the survey) by task and by session. A) Navigation only task, B) Cycling only task, and C) Dual-Task condition during which participants concurrently performed aerobic cycling exercise with the virtual navigation task; $*p < 0.05$.

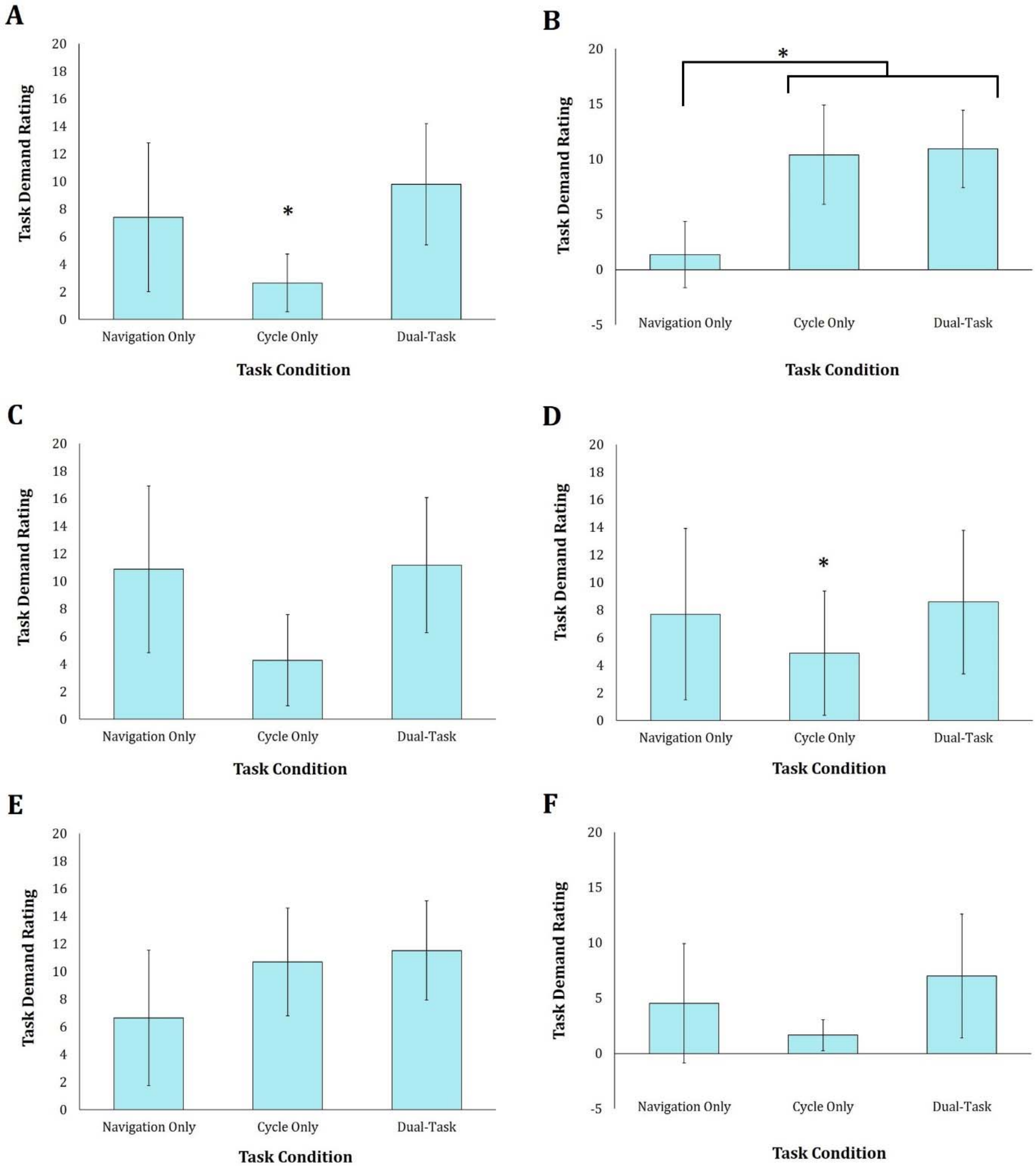


Figure 4.8: Average NASA TLX scores (+sd) across all sessions for each of the individual domains within the survey: **A**) Mental, **B**) Physical, **C**) Temporal, **D**) Performance, **E**) Effort, and **F**) Frustration. Note that for the Performance domain, a lower score indicates better perceived performance, while a higher score indicates poorer perceived performance; *p < 0.05.

Participants were also given a visual analog scale (VAS) in order to rate the difficulty of the virtual navigation task. A two-way ANOVA was used to examine if there were differences in perceived virtual navigation task difficulty based on the task (navigation only vs. dual-task) and also based on the session order. The average (± sd) VAS score for the navigation only session was 3.0 ± 2.6 and was 4.3 ± 1.9 for the dual-task session. The average (± sd) VAS score for the first session in which participants were exposed to the virtual navigation platform (regardless of whether the task was navigation only or dual-task) was 3.9 ± 1.7, and was 3.4 ± 2.8 for the second session of exposure to the virtual navigation platform. When examining differences in VAS scores based on task (navigation only versus dual-task), there was no significant difference ($F_{1,26} = 4.17$ ($p = 0.29$)). When examining differences in VAS scores based on session order presentation of virtual navigation, there was no significant difference ($F_{1,26} = 1.52$ ($p = 0.43$)). Lastly, upon examination of a possible interaction effect of task (navigation only vs. dual-task) and session order, there was also no significant difference ($F_{1,26} = 2.57$ ($p = 0.36$)).

4.7 Discussion

The objective of this study was to examine dual-task trade-offs that were likely to occur when coupling aerobic cycling with a virtual navigation task in a concurrent manner. Mean cycling cadence was higher when participants were required to simply cycle when compared to when they were asked to complete the concurrent exercise-executive challenge. However, there was no statistical difference in mean cycling variability between the two tasks, despite the large difference between values. With respect to physiological metrics, there was no difference in mean heart rate over the duration of the cycling only and dual-task conditions.

While there was a statistically significant difference in mean cycling cadence between the cycling only and the concurrent exercise-executive challenge, this difference may not be biologically significant as cycling only mean cadence was 64.59 ± 6.53 RPM while it was 58.18 ± 9.06 RPM for the dual-task paradigm. Furthermore, there was no difference in power output between the two task conditions and there was no difference in heart rate between the two task conditions. The lack of differences in these other behavioural and physiological measures suggest that there may not be a difference or a trade-off in the coupling of aerobic cycling exercise with this specific virtual navigation task, at least with respect to the ability to simultaneously perform both tasks while maintaining a desired heart rate when examining the performance over the entirety of the 20 minute time block. The lack of trade-off may be a result of age group of participants studied; these young healthy adults may be more capable of dual-tasking or multi-tasking due to their extensive experience of growing up performing multiple tasks while moving and/or using technology (Allen et al., 2014). One theory commonly used to explain dual-task interference is that of a *serial bottleneck*, meaning that dual-task costs result from the ability to only process information from one task at a time due to processing capacity limitations (Abernethy, 1988; Plummer & Eskes, 2015). Another prominent model is the *capacity sharing model*, in which information from multiple tasks can be processed in parallel, still with a limited processing capacity, and therefore the executive resource capacity may be allocated differentially to one task over the other as influenced by characteristics of the task(s) themselves (Abernethy, 1988; Plummer & Eskes, 2015). Due to the natural links between locomotor activity and navigation tasks, this dual-task paradigm may be utilizing more of a capacity sharing model, and therefore may enable individuals to more readily, and more rapidly differentially allocate resources between the exercise and executive tasks. Imaging studies have suggested that when individuals use serial processing strategies during a dual-task paradigm the lateral prefrontal cortices are recruited, whereas when individuals use a parallel means of processing dual-task information, the striatum and basal ganglia are recruited (Yildiz & Beste, 2015). Additionally, when individuals are performing a well-practiced and more automated portion of a dual-task paradigm, mediation of this task is supported by the basal ganglia (Yildiz & Beste, 2015).

It is also important to note individual variability in performance. Dual-task cost was calculated as DT Cost = ([dual-task performance – single task performance] / single task performance)*100% (Falbo et al., 2016). The trade-off, as a percentage change in cycling cadence is quite different between individual participants, as seen in Figure 4.3. Therefore it will be important to understand how dual-task trade-off changes over time as a function of repeated exposure to the task. Practice enables individuals to learn and improve their performance of a task, in this case, the trade-off in cycling cadence that occurs when performing a virtual navigation task in conjunction with the aerobic challenge. Dual-task trade-off with respect to cadence variability will also be influenced by the unique control challenges presented as a function of the design of this virtual navigation task. The navigation task has components where individuals are travelling along a straight line paths interspersed with turns and direction changes required in order to comply with task instructions. Therefore, dual-task trade-offs, when examined as a whole over the 20-minute exercise bout may in fact be driven by the more transient moments of slowing or ceasing pedaling in order to make a turn or to turn around at the associated pin location.

While these more global measures of behavioural and physiologic performance during the cycling only and dual-task conditions do not demonstrate differences between the tasks, there are likely transient points in time where differences in performance exist. It is likely that variability in cadence exists when performing the exercise task by itself due to some interaction of individual fitness level and the pacing strategy chosen (Atkinson et al., 2007). This variability may be further augmented by the addition of the secondary virtual navigation task, as now individuals must engage with the navigation task and make decisions about where to travel to next and how to get there (Wiener et al., 2009; Wolbers & Hegarty, 2010). These decision points are likely to occur at intersections or junctures where a turn must be made, and it is likely that transient moments of dual-task interference occur at these decision points (Anderson-Hanley et al., 2012). These transient moments are not captured in the global measures of dual task trade-offs, but may provide further insight into how individuals choose to prioritize (or if they choose to prioritize) the executive task over the exercise task.

The lack of difference in rate of perceived exertion between the tasks indicates that the addition of the virtual navigation task did not unduly add to the perception of physical exertion or stress perceived when performing exercise. This of course was of concern, as the addition of a secondary task may have caused the perception of exertion to increase, indicating that participants felt as though they were working much harder physically due to the addition of an executive task. This study found that rates of perceived exertion were lower (though not statistically) for the first 15 minutes of exercise in the concurrent exercise-executive challenge when compared to cycling alone (see Figure 4.5 B). This may suggest that instead of the secondary task adding to a sense of physical fatigue, it may help to reduce the perception of physical fatigue by providing individuals with a distraction from the unpleasant or negative effects of exercise, such as pain and discomfort (Anderson-Hanley et al., 2014). This was further supported by the psychometric data from the NASA Task Load Index. There was no statistical difference in the perception of the physical workload between the exercise alone and the concurrent exercise-executive challenge. If the addition of a secondary executive task acts as a distractor from any pain or discomfort associated with exercise, it may increase adherence to an exercise or rehabilitation regime, and may enable individuals to partake in exercise for longer durations, both within an individual session and over time (Anderson-Hanley et al., 2014; Shatil, 2013).

Interestingly, while this study provides evidence to suggest that individuals do not perceive the physical demands of the exercise vs. exercise-executive challenge to be different, they did perceive the mental demands of the tasks differently. The results from the NASA Task Load Index demonstrated that the mental demands of the cycling only task were significantly less than that of the navigation only or the dual-task paradigm. This study examined fit, young healthy adults. As a result, these individuals were likely experienced with participating in physical activity and / or exercise, and found the mental demands of the exercise to be low. The lack of difference in mental demand between the navigation only task and the dual-task paradigm suggests that the combination of the exercise with the executive challenge did not further increase the mental load on participants. This is also of importance for consideration. While combined exercise-executive training tasks become more prevalent, it will not only be important to ensure that the dual-task paradigms do not increase the perception of physical fatigue (discussed above), but that they do not increase the perception of mental fatigue as well. NASA Task

Load Index scores summed across all six domains (mental, physical, temporal, performance, effort & frustration) did show that the dual-task paradigm of virtual navigation combined with aerobic cycling was more executively demanding that the cycling only and navigation only tasks. This suggests overall, the concurrent exercise-executive task was more executively demanding than either condition alone. Therefore, as future research and rehabilitation programs become available, the physical, mental, and combined demands on participants will need to be of consideration to researchers and rehabilitation specialists.

This task design of concurrently coupling aerobic cycling with a virtual navigation task, and its associated metrics of behavioural performance, physiological performance and psychometric perceptions are likely to be different in older adult populations and patient populations. Research in older adults examining dual-task trade-offs with respect to gait have demonstrated that dual-task training paradigms improve gait performance with respect to an increase in gait speed and a reduction in step variability, as well as performance within the executive task / domain that was trained (Falbo et al., 2016; Schaefer & Schumacher, 2011). It may be possible then, that older adults or patient populations may be able to practice with multi-tasking using this exercise-navigation task in particular, to improve both their aerobic and executive capacities.

4.8 Conclusion

This study provides insight into the behavioural and physiologic metrics of a concurrent exercise-executive challenge. Specifically, the results from the study demonstrate while some metrics of the behavioural performance of the exercise task may be different between the exercise only and the exercise-executive task, young healthy adults were able to maintain a global work rate within a target heart rate zone that would promote positive aerobic adaptations. Furthermore, this task did not increase perceptions of physical or mental exertion when the cycling and navigation task were combined, suggesting that the dual-task training paradigm may not increase a sense of fatigue for future participants. However, this study only examined performance measures based on singular exposure to the tasks. This in turn speaks to the need to examine what changes, if any, occur when participants are repeatedly exposed to the tasks.

Chapter 5: Study 4

Repeated Exposure Effects of Dual-Task Trade-Offs of Concurrent Cycling and Virtual Navigation

5.1 Introduction

Improving executive function is an important outcome for many individuals, including those who are aging and those who are part of a clinical population. Training executive function with computerized training programs is one means to improve executive function (Kelly et al., 2014). However, these training paradigms tend to train only a single domain of executive function within a training task, and are typically not performed in an ecologically valid scenario. This may account for the variability in the literature surrounding the possibility of transfer effects, and the general finding that training a single domain of executive function at a time promotes little transfer of improvement to executive functions in the untrained domains, or to more global measures of cognition (Tait et al., 2017). Furthermore, solely training executive function does not appear to promote transfer to everyday functioning as seen in activities of daily living (Tait et al., 2017).

In addition to executive training, research within the past decade has demonstrated that aerobic exercise, in and of itself, has positive effects to executive function. Various research has shown positive behavioural and / or physiological changes as a result of both single exercise bouts and chronic exercise participation (Bamidis et al., 2015; Lauenroth et al., 2016). Since both executive and exercise training improve executive function, researchers have explored the idea of having individuals perform both aerobic exercise and executive training together. The premise behind the combined training is twofold: 1) the aerobic exercise promotes the proliferation of neuroplasticity and neurogenesis, while the executive training promotes the incorporation of neuroplastic and neurogenic change into already existing neural networks, and 2) there is the potential to enhance ecological validity of the training paradigm, which may in turn lead to transfer effects of training executive function and transfer to ADLs (Tait et al., 2017).

Literature has examined both sequential and concurrent training paradigms. From the concurrent training paradigms, the concept of exergaming emerged as a promising new methodology for simultaneously improving executive function and functional ability. Exergaming combines exercise and executively 'engaging' activities through videogames such as Dance Dance Revolution® and Nintendo Wii™ (O'Leary et al., 2011). Exergaming can also be achieved by combining stationary cardiovascular training equipment with a screen and software that enables users to interact with a virtual environment (O'Leary et al., 2011). While exergaming has shown potential for improving executive function and participation adherence, generally only metrics associated with executive function are reported. Exergaming can also be implemented using more traditional aerobic exercise equipment and coupling it with a computer interface to enable individuals to interact with an executive training task. For example, Grealy et al. (1999) had traumatic brain injury (TBI) patients partake in a rehabilitation program that concurrently coupled aerobic cycling exercise with travelling through a virtual environment, in the hopes that this would promote both behavioural and physiological improvements in brain function. They found that individuals improved their learning ability in visual and auditory tasks but did not show improvements in memory tasks when compared to the cycling only group. (Grealy et al., 1999). Additionally, the authors also noted that adherence to the rehabilitation protocol was greater in the concurrent exercise-executive challenge group compared to the exercise alone group (Grealy et al., 1999).

Improvements to executive function may in fact be partially related to the learning of, and the novelty of the new skill of concurrently coupling aerobic exercise with executive tasks. The previous studies in this thesis have implemented virtual navigation for the following reasons: 1) it naturally couples with locomotor rhythm, 2) it requires multiple executive domains to working simultaneously to complete the task, and 3) taken together it presents an ecologically valid task. The main promise of concurrent exercise-executive training is that it might lead to an additive effect on outcome measures of executive function while also benefiting physical health (Tait et al., 2017). If an additive effect to executive function occurs in tandem with maintenance or improvement to cardiovascular function then this may be a viable training model to extend into clinical rehabilitation (Bherer, 2015; Tait et al., 2017).

However, one of the challenges of concurrently coupling aerobic exercise with a secondary executive task is the likely dual-task trade-off effect. One of the goals of aerobic exercise is to maintain or improve aerobic capacity (Wilson et al., 2016). Aerobic exercise is important for individuals of all ages, as it is known to mitigate the chances of developing CVD, diabetes or metabolic disease (Bherer, 2015; Wilson et al., 2016). Aerobic exercise is also an important component of many rehabilitation protocols, including musculoskeletal rehabilitation, cardiac rehabilitation and stroke rehabilitation (Sibley, et al., 2008). While these exergaming protocols may be beneficial to executive function, what benefits are they imposing on the cardiovascular system? If there is little to no aerobic benefit, than individuals may need to partake in an aerobic exercise program that is separate from, and in addition to, the concurrent exercise-executive challenge paradigm. What is unknown is how this dual-task paradigm of exergaming effects metrics of the exercise and if it promotes improvements to cardiovascular capacity.

However, the previous study only exposed participants to the dual-task paradigm once, as a means to examine dual-task effects. Typical rehabilitation protocols or clinical protocols occur over repeated sessions over time. Therefore, while trade-offs may be large initially, it is likely that individuals improve their performance with more experience, which may in turn mitigate the magnitude of the dual-task trade-off effects to both the behavioural and physiological metrics of the exercise. There is the possibility that average cadence increases and that cadence variability decreases over repeated exposure, meaning that individuals would be better able to maintain a target heart rate and achieve cardiovascular benefits of exercise. It is also possible that their ability to navigate would improve with repeated exposure to the task. Lastly, it is also likely that as experience mitigates the dual-task effect, participants may not feel as fatigued at the end of later sessions as they do at the end of the first session when exposed to multiple training sessions. Therefore, it is important to know how repeated exposure to the task effects behavioural and physiological changes over time before deciding if this is a task that can be implemented in a rehabilitation or therapeutic setting.

Executive functions interact with motor function in order to enable us to perform goal directed behaviour, and it has been suggested that sensorimotor adaptation or learning can be effected by the performance of a secondary, executively demanding task (Taylor & Thoroughman, 2008). This leads to questions regarding the ability of young healthy adults to adapt their motor patterns based on their familiarity with the dual-task paradigm based on repeated exposure to the task. Furthermore, Janssen & Brumby (2015) examined multi-tasking effects in individuals who were asked to complete two separate tasks but could only perform one task at a time. Therefore, the decision to switch between tasks was solely up to the participant. They found that the decision to switch between tasks was dependent on 3 factors: individual skill level of the participant with respect to the given task, the characteristics of the task, and incentives offered by the researcher (Janssen & Brumby, 2015). Again, it is possible that repeated exposure to the dual-task paradigm of cycling while performing a virtual navigation task in Google Earth may change individual skill level within participants. While no incentives were offered by the researcher in this study, there is the incentive to complete the task within the given timeline – i.e. there is a sense of competitiveness that is inherent to the task. Adaptations that may reflect improvements to individual skill level based on the task include a reduction in cadence variability and increased overall cycling cadence, as well as an increase in heart rate (as a result of increased cadence and decreased cadence variability over time). This may also be reflected in the perceived difficulty of the task, such that improvements gained through repeated exposure to the dual-task paradigm would be reflected in a reduction in overall task difficulty perceptions.

Therefore, the primary objective of this study was to explore the change in dual-task trade-off over repeated exposure to the training regime. It was hypothesized that the dual-task trade-off effect observed during the concurrent exercise-executive challenge would decrease over repeated exposure. Specifically, it was hypothesized that cadence variability would decrease, and average cadence would increase, thus promoting the ability to maintain a target heart rate. With regard to psychometric data, it was hypothesized that perceptions of fatigue and mental effort would decrease over repeated exposure to the task.

5.2 Methods

Participants

Eight healthy young adults (5 females, 3 males) participated in the study (aged 19 – 23, mean (± sd) age = 21.1 ± 1.2 years, height = 168.8 ± 11.1 cm, and weight = 64.3 ± 12 kg. All participants completed the Get Active Questionnaire (GAQ), provided self-reports of educational background, exercise participation level, video game experience and navigational experience. Participants reported no neurological or musculoskeletal conditions that would affect their ability to perform the exercise protocol required of the experiment, including being non-smoking, and not pregnant. Participants also had normal or corrected to normal vision with no reported visual impairments (e.g. colour blindness) in order to perform the computerized virtual navigation task. This study received clearance from the Office of Research Ethics at the University of Waterloo, and all participants provided written consent prior to study participation. Details about the participants can be found in Table 5.1.

Participant Demographic Information

Category	Female	Male	Cohort Combined
Age (years)	21.8 ± 0.8	20 ± 1	21.1 ± 1.2
Height (cm)	162.4 ± 8.5	179.5 ± 3.3	168.8 ± 11.1
Weight (kg)	58.1 ± 11.1	74.7 ± 1.2	64.3 ± 12
VO_{2peak} (mL/kg/min)	38.6 ± 6.1 (30.2 – 43.9)	49.1 ± 7.1 (42.8 – 56.8)	41.4 ± 8.7 (30.2 – 56.8)
Target Heart Rate (bpm)	130 ± 17	127.7 ± 11.6	129.1 ± 14.3
Preferred Cadence (RPM)	54 ± 6.5 (50 – 65)	65 ± 13.2 (55 – 80)	58.1 ± 10.3 (50 – 80)

Table 5.1: Participant demographic information by sex and as a combined cohort. Values are means ± standard deviation. Values that are in brackets are the range of values within the category.

Overview of General Experimental Set-Up

Participants attended the lab on seven separate occasions. During the intake session, participants completed a demographics questionnaire to attain information regarding their educational background, videogame play experience, and navigation experience. Perception values were combined to create a composite score for Overall Navigation Ability and a composite score for Overall Videogame Play Ability in order to gauge participant's perceptions at the regularity with which they perform navigation type tasks and videogame type tasks. The demographics questionnaire can be found in Appendix F. A summary of the findings from the demographics questionnaire can be found in Table 5.2.

Vision was tested using a Snellen eye chart at a distance of 3 meters, and also using the Mars Contrast Sensitivity test. All participants had visual acuity of 20/15 or better as determined through a Snellen Eye Test, and binocular Mars Contrast sensitivity of 1.68 or better. Participants were familiarized with the virtual navigation task that would be performed in Google Earth. A practice route in the city of Toronto was used to familiarize participants with the virtual graphics, the program controls, and the instructions for the virtual navigation task. Finally, participants performed a maximal oxygen uptake (VO_{2max}) test in order to prescribe the appropriate exercise intensity for later experimental sessions.

Experimental sessions 1-6 all consisted of performing approximately 20 minutes of each of the following conditions: cycling exercise only, virtual navigation only, and a dual-task condition that concurrently coupled cycling exercise and virtual navigation. The order of performance of each task was block randomized within each session and within each participant. At the beginning of each experimental session a 5 minute resting heart rate was recorded. Additionally, participants were given a short practice navigation task in order to re-familiarize them with the controls, and the instructions of the task. The aerobic intensity of the exercise for both the cycling only and the concurrent exercise-executive task was set to the heart rate that corresponded to 50-60% of the VO_2 reserve as determined from the VO_{2max} testing procedure.

Participant Questionnaire Data

Category	Female	Male
Handedness: Right/Left	5/0	3/0
Program: Kinesiology / Other STEM	3/2	1/2
Level of Study: Undergraduate / Graduate	5/0	3/0
Self Reported Exercise Hours / Week:	2 ± 1.2	2.7 ± 2.1
Hours per week driving:	2.1 ± 3.4	3.3 ± 4.1
Hours per week as a passenger:	1.7 ± 0.8	1 ± 1
Hours per week on Public Transit:	2.1 ± 2.4	3 ± 2.6
Self Reported Video Game Player: Yes / No	0/5	2/1
Video Game Preference: Immersive / Non-Immersive	N/A	1/1
Hours per day playing video games:	N/A	0.6 ± 0.2

Table 5.2: Summary of the findings from the participant demographic questionnaire by sex. Values are means ± standard deviation, or a count between the two categories listed.

Psychometric Questionnaires

Upon arrival to the lab, participants rated their overall level of fatigue using the Rating of Fatigue (ROF) scale (Micklewright et al., 2017) (Appendix B). This measure was taken again upon completion of all testing procedures. After each individual task manipulation within the session, participants completed the NASA Task Load Index (NASA-TLX) (Appendix C). The NASA-TLX is a questionnaire that examines mental workload in the following six domains: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration (Hart & Staveland, 1988). Domain names, along with a prompt explaining the domain, are provided for participants above a 20-point Likert scale which ranges from “very low” to “very high”, with the exception of the Performance domain, which ranges from “perfect” to “failure” (Hart & Staveland, 1988). Higher values indicate greater mental workload and poorer performance within each individual domain scale, as well as when the sub-scaled are summed to create an overall composite score.

A Visual Analog Scale (VAS) was also designed and administered to participants after each navigation task that was performed. Participants were asked to rate how difficult they found the virtual navigation task from “no difficulty” (score of zero) to “extremely difficult” (score of 10). Participants were also given the opportunity to provide feedback on how they found the task, and the strategies that they used to complete the task.

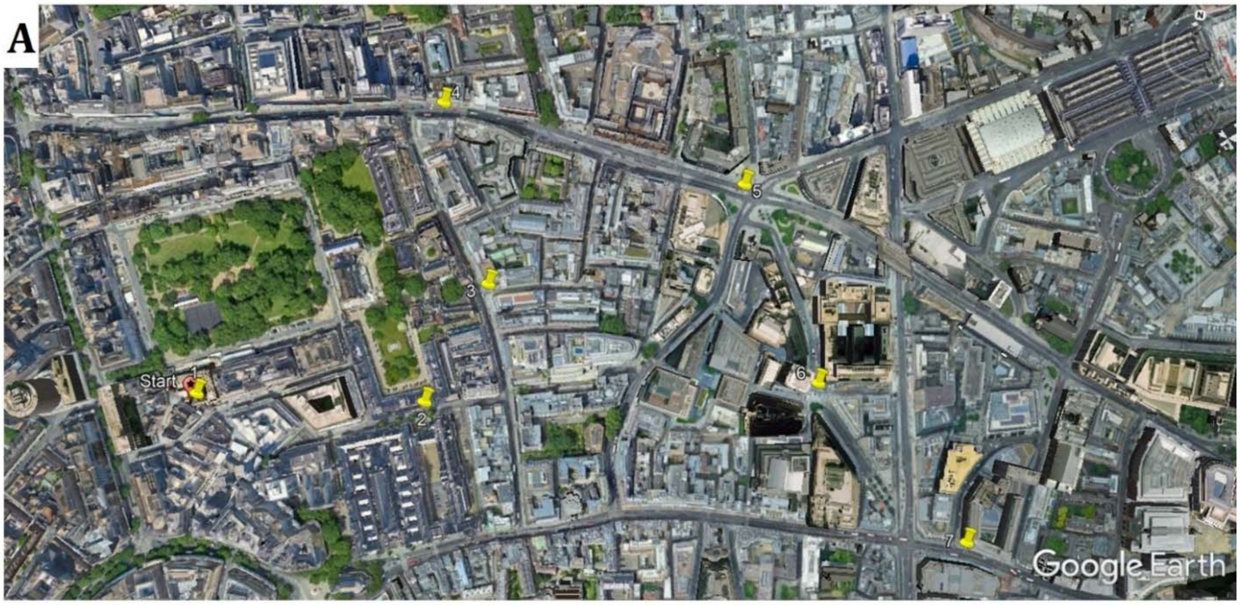
Virtual Navigation Tasks

The virtual navigation tasks were performed using the free download platform of Google Earth in the 3D rendered version of street view. This provides a first person view of movement through the virtual environment. In the intake session and during the navigation only block within each experimental session, movement through the environment was performed using a keyboard: up and down arrow keys to move forward and backward, respectively, while left and right arrow keys to make leftward and rightward turns, respectively.

At the beginning of each experimental session, participants completed a practice virtual navigation task to re-familiarize themselves with the controls and the task instructions. These practice routes were completed in the city of Chicago IL, United States of America, and there were three routes that were used in the following order: Sessions 1 &

4 practice using route 1, Sessions 2 & 5 practice using route 2, and Sessions 3 & 6 practice using route 3. The practice routes had a total of three pins.

The experimental virtual navigation tasks took place in the city of London, England (UK). See Figure 5.1 for an aerial view of the routes used, as well as a sample first person view. For all routes, participants were given a start point, a virtual pin with the number "1" attached to it that was placed in the virtual environment. Participants were placed in the virtual environment so that they were in the direction necessary to move towards Pin 2 (i.e. Pin 2 was not behind them). Participants were instructed to find Pin 2, and then return to Pin 1. Once returning to Pin 1, they were to turn around, and then proceed to move from Pin 1, to Pin 2, and then on to Pin 3, and again return to Pin 1 connecting through Pin 2 along the way. Participants were informed that this process was to be repeated until 1) all pins (total of 7) had been found and they had successfully returned to Pin 1, or 2) when their 20-minute time limit was reached. Information regarding the route details can be found in Table 5.3.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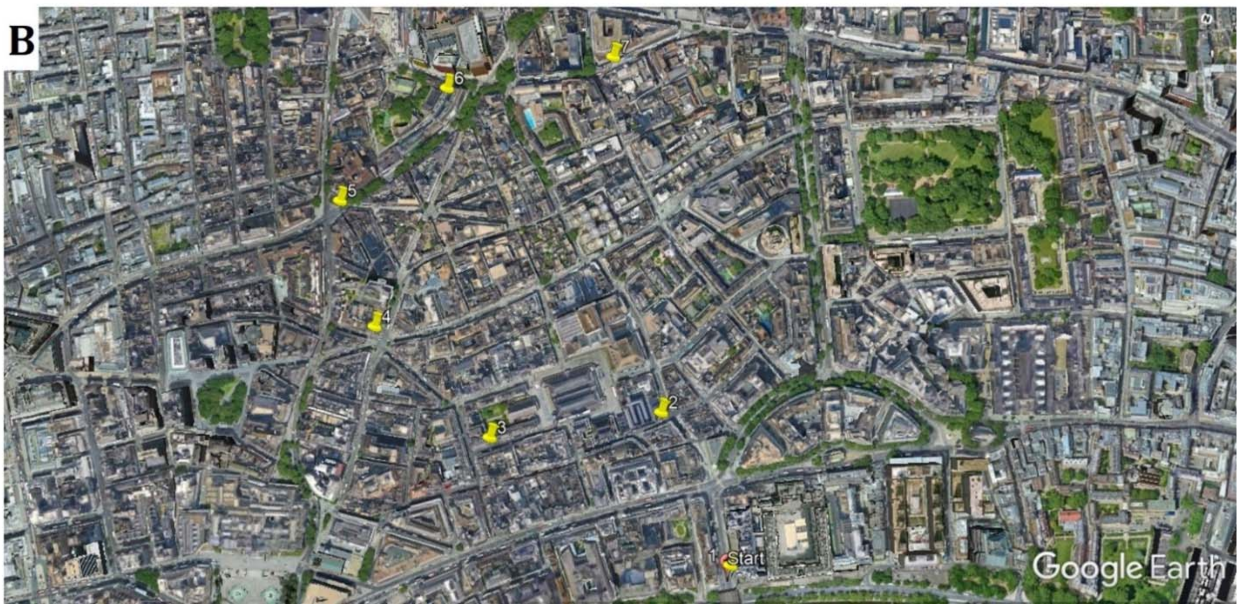
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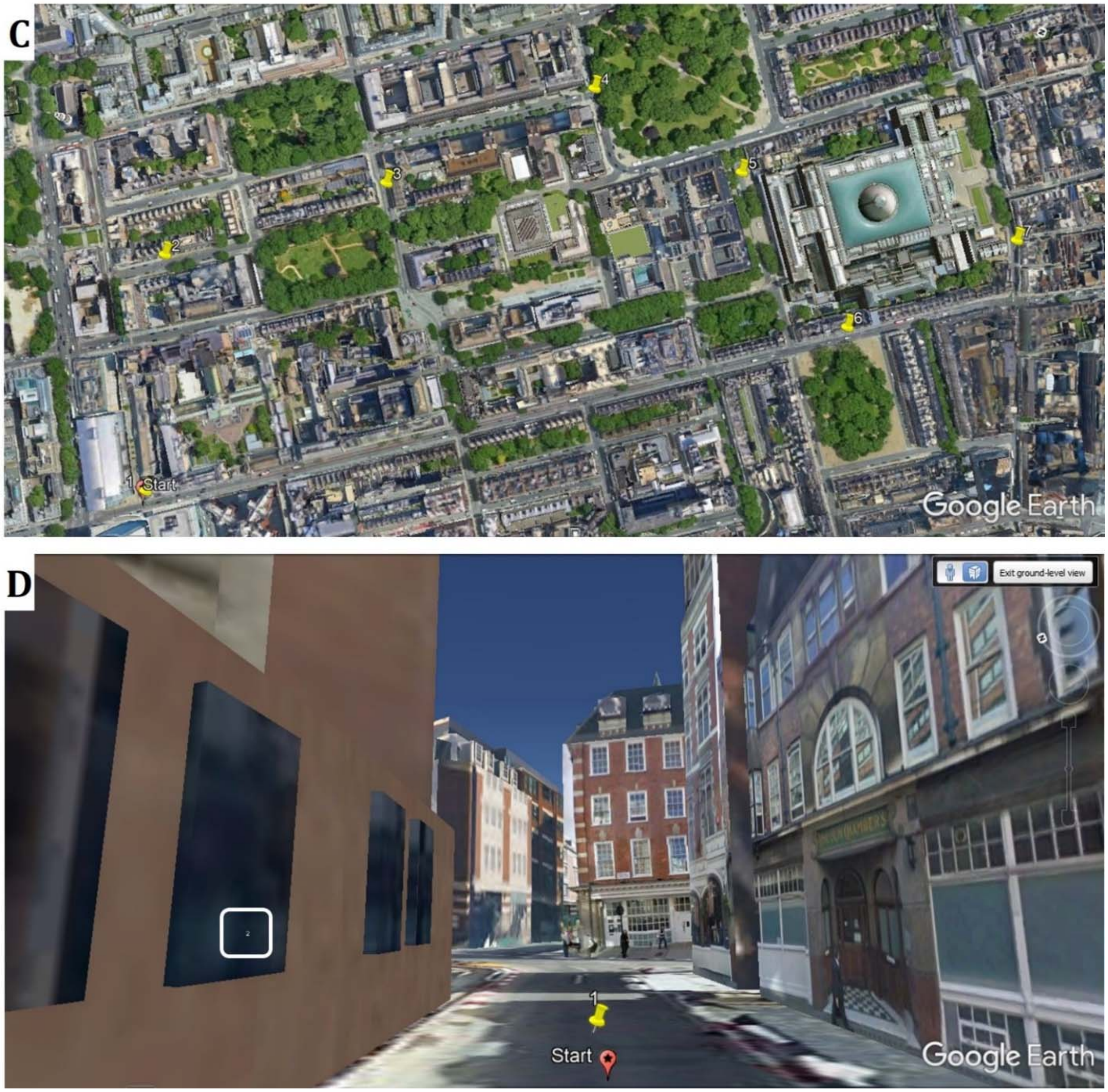


Figure 5.1: Aerial view of Google Earth routes; **A**) Route 1 in the forward direction; **B**) Route 2 in the forward direction, and **C**) Route 3 in the forward direction; **D**) First person view of the virtual navigation task in the 3D rendered setting of Google Earth. The white box has been added to highlight where Pin 2 is, as it can be seen in the distance from Pin 1.

Three routes were designed (routes 1, 2 and 3) and participants completed them in a forwards (F) and backwards (B) order, making for a total of six routes: 1F, 1B, 2F, 2B, 3F and 3B. For the backwards routes, the pins were re-numbered in Google Earth so that participants always started at Pin 1, and were working on making their way to Pin 7. The routes were block randomized between participants and between sessions. Within a session, participants would perform the same route in the forwards and backwards manner, but were not informed that this was the procedure. Upon study completion, participants completed each of the six routes once each for both the navigation only task and the dual-task conditions.

Google Earth Route Information

Route	Total Route Distance (km)	# Left Turns	# Right Turns	Total # Turns	Mean Distance (m) between Pins	SD Distance (m) between Pins
Practice Routes:						
Chicago 1	2.180	2	1	3	390.3	96.8
Chicago 2	1.988	1	1	2	340.3	64.4
Chicago 3	2.305	1	1	2	374.4	101.1
Experimental Routes:						
London 1	11.834	5	3	8	274.2	64.2
London 2	11.341	4	5	9	299.2	41.1
London 3	11.006	3	3	6	263.9	64.3

Table 5.3: Summary of the Google Earth route information. Total route distance is the total distance the participant would travel if participants completed the task along an ideal route. The number of turns are depicted as the number of turns one would take when travelling from Pin 1 to Pin 7 a single time, and ceasing the task at Pin 7.

Exercise Only Session

For the cycling only block, participants were asked to cycle on a recumbent cycle ergometer (Technogym® 700, Technogym, USA Corp.). Participants were given a 5 minute warm-up period in order to reach their target heart rate which was the heart rate that corresponded to 50-60% of their VO_2 reserve as determined from their VO_{2peak} attained from the maximal graded exercise test, and then continued to exercise for an additional 20 minutes. Rate of perceived exertion (RPE) was recorded every 5 minutes throughout the exercise session using the 10-point Borg RPE scale (Appendix A).

Concurrent Exercise & Virtual Navigation

This intervention combined the above tasks. Again, participants were then given a warm-up period to enable their heart rate to achieve 50-60% of their VO_2 reserve. Upon the start of the exercise period, participants were placed in Google Earth and asked to perform the same task as outlined above, along the same route as they performed for the navigation only task, only this time the route and pin numbers are reversed (e.g. Pin 7 now becomes Pin 1, and so forth). During the concurrent cycling-navigation block of each session a joystick was connected to the computer, and the bike was fitted with a magnetic sensor so that the forward pedalling motion of the bike caused the forward motion within the Google Earth environment, while a hand-held joystick enabled participants to make left and right turns. Again, RPE was recorded every 5 minutes.

VO_2 Max Testing

To perform VO_{2max} testing, the Vmax® Encore Breath-by-Breath System (Care Fusion, SanDiego, CA) was used in conjunction with a Burdick EK10 electrocardiograph and an upright electronic cycle ergometer: VIAsprint® 200P Cycle Ergometer (Ergoline GmbH, Bitz, Germany). In order to attain heart rate, the CM5 electrode placement was used with a single electrode in each of the following locations: manubrium, 5^{th} rib on the right, and 5^{th} rib on the left, both inferior and lateral to the nipple line. For female participants, this was the bottom and lateral edge of a sports bra. Skin sites were cleaned using NuPrep abrasive gel, and then again using alcohol swabs to remove any remnants of the gel. Participants were then assisted onto the cycle ergometer and the seat height was adjusted so that there was a slight bend in the knee when the leg was at full extension. Participants were then fitted with the headpiece and flow sensor to collect ventilation values. Participants sat quietly on the bike for 2 minutes to attain resting values, and were then given a 2 minute warm up at a workload of 50-75 Watts, at a cadence of their choice. This cadence was recorded for use during future experimental sessions. There was then a 1 minute rest period to ensure the participant was comfortable and to ensure all equipment was working properly. Then participants began the VO_{2max} testing procedure. Work rate started at 25 Watts, and increased in a step-wise manner by 25 Watts every 60 seconds. Participants were asked to maintain the cadence that they cycled at during the warm-up. Test cessation criteria were the following: a) volitional cessation by the participant, b) cadence dropped 10 RPM below the preferred cadence for a period of 10 seconds or longer, c) respiratory exchange ration ≥ 1.1, d) heart rate failed to increase with continued increase in work rate or e) signs / symptoms experienced by the participant indicated cessation of the test.

The Vmax Vision SensorMedics Inc. software provides continuous analysis of a multitude of variables including: oxygen consumption (VO_2), heart rate (HR) and the respiratory exchange ratio (RER). These variables are displayed in real time during testing, and are stored for later processing and analysis. Additionally, rate of perceived exertion

(RPE) using the 10 point Borg Scale (Appendix A) was taken at the end of each work rate. In offline analysis, VO_2, HR and RER were be averaged into 20 second bins. To determine if VO_{2peak} was achieved, common criteria include: VO_2 increase of 2.1 mL/kg/min or less for an increase in workload, RER > 1.1, RPE peak > 9 and HR > 90% age predicted max heart rate (220-age). In order to achieve a true VO_{2peak}, at least 2 of these criteria must be met during the test.

5.3 Instrumentation & Data Acquisition

The recumbent cycle ergometer was equipped with a voltage box that created a voltage pulse with every revolution of the wheel. This signal was recorded constantly throughout the exercise blocks and stored for future analysis. Participants were equipped with a heart rate monitor (Bittium Faros, Bittium Biosignals Oy/Mega Electronics, Kuopio, Finland) that recorded heart rate continuously throughout each task to examine heart rate changes as a function of changes to cadence. Electrocardiography (ECG) was collected using self-adhesive electrodes from three electrode sites: 5 cm to the left and to the right of the inferior portion of the manubrium, and on the 5-6th rib lateral to the nipple line on the left hand side of the participant. Skin sites were first abraded with NuPrep skin preparation gel and then cleaned with rubbing alcohol. Heart rate was also monitored continuously throughout exercise with a Polar Heart Rate Monitor (Polar Electro Oy, Kempele, Finland) and was monitored by the researcher, not the participant.

Within the Google Earth environment, the program enables the video recording of navigation performance. From this video file, latitude and longitude position is recorded twice per second. This data is then used to map the route that participants traveled and compute movement details (distance, time).

5.4 Data Analysis

Data was analyzed using a custom built LabView program (National Instruments, Austin TX, USA). Revolutions per minute was determined by the cycle pulse box that was embedded next to the fly wheel of the stationary bike. Power output was determined over the course of the exercise based on the cadence of the individual and the resistance level setting on the cycle ergometer. Cadence means were calculated as individual cycle time for each revolution, and then taking the reciprocal to achieve a value in revolutions per minute. These values were then be averaged to examine cadence over time of the exercise bout. Standard deviation was then calculated from this average, and power output (Watts) was calculated using these RPM values as well. Cadence variability was calculated as the average standard deviation of cycling cadence in RPM across the individuals. Heart rate files were first converted from an EDF file to a CSV file. Heart rate data was run through a dual-pass, bandpass, second order Butterworth filter, with low and high frequency cut-offs of 500 and 1 Hz, respectively. Heart rate average and standard deviation were then calculated for the 20 minutes of exercise when participants were to be at 50-60% of their VO_2 reserve.

The video data from Google Earth was also processed with a custom built LabView program to calculate the overall distance travelled from latitude and longitude data. The joystick data was processed in LabView in order to determine time points when turns were made. This information was used to examine durations of time spent turning or making adjustments to heading as a function of total travel time. The overall distance that participants travelled in the Google Earth environment was calculated for both the navigation only and concurrent exercise-executive challenge task conditions (see equation from Study 2 on page 84). Additional measures included the total time spent moving forward within the environment, the total dwell time (i.e. time not moving forward, rather remaining in one place to look around), as well as the total turn time. Total turn time includes a summation of turns or adjustments that occurred while moving forward and while not moving forward.

5.5 Statistical Analysis

Two-way repeated measure ANOVAs were used to examine potential differences in exercise performance between tasks (cycling-only and dual-task) and session (1-6). These comparisons include RPM mean, RPM variability and heart rate in cycling alone vs. concurrent cycling with virtual navigation. Two-way repeated measure ANOVAs were used to examine potential differences in navigation performance between tasks (navigation only and dual-task) and session (1-6). Additionally, two-way repeated measure ANOVAs were used to examine potential differences in psychometric data across tasks (navigation only, cycling only, and dual-task) and session (1-6). Comparisons of psychometric data were made to examine possible changes to perceived workload and cognitive demands due to the different task conditions. Where necessary, a Tukey's post hoc test was used to determine differences between groups. Significance level was set to $\alpha = 0.05$. Resting heart rate data was missing for one individual for one session, as were two individual task blocks of heart rate data within one session. Four trials of navigation distance data were missing from the analysis as were two trials of navigation time. These missing data points were due to technical difficulties of the equipment.

5.6 Results

Physiological and Behavioural Metrics of the Exercise

Contrary to the hypothesis, there was no difference in average cycling cadence as a result of task (cycling only or dual-task) ($F_{1,7} = 0.00$ ($p = 0.99$)), as a result of Session (1-6) ($F_{5,7} = 0.63$ ($p = 0.69$)) or an interaction effect of task by session ($F_{5,72} = 0.68$($p = 0.66$)). Average cycling cadence was 64.7± 9.8 RPM during the cycling only task and was 61.3 ± 12.7 RPM during the dual-task paradigm, when collapsed across sessions. Average cycling cadence during the cycling only task throughout sessions 1-6 were as follows: 65.2, 63.8, 64.3, 64.8, 65.1, and 65.1 RPM. Average cycling cadence during the dual-task paradigm throughout sessions 1-6 were as follows: 59, 60.5, 60.2, 61.9, 63.4, and 62.8 RPM (see Figure 5.2).

The same findings were true for cadence variability; there were no statistically significant differences between tasks ($F_{1,7} = 27.46$($p = 0.12$)), between sessions ($F_{5,7} = 3.15$($p = 0.12$)) or an interaction effect of task by session ($F_{5,72} = 1.95$($p = 0.24$)). The average variability in cadence, as measured through the average standard deviation in cadence across the exercise bout, was 2.4 for the cycling only task and was 7.7 for the dual-task paradigm. Average cadence variability during the cycling only task throughout sessions 1-6 were as follows: 2.7, 2.5, 2.3, 2.4, 2.5, and 2.2 RPM. Average cadence variability during the dual-task paradigm throughout sessions 1-6 were as follows: 8.4, 8.6, 8.1, 7.6, 6.6, and 6.6 RPM.

Power output was also not different across task conditions of cycling only vs. dual-tasking. There were no statistically significant differences in power output between tasks ($F_{1,7} = 18.82$($p = 0.14$)), between sessions ($F_{5,7} = 0.88$($p = 0.55$)) or as an interaction between task and session ($F_{5,72} = 1.20 (p = 0.42)$). Average (± sd) power output (Watts) was 80.1 ± 30.7 for the cycling only task and was 77.7 ± 32.6 for the dual-task paradigm, when collapsed across sessions. Average power output during the cycling only task throughout sessions 1-6 were as follows: 80.6, 79.2, 79.6, 80.7, 79.5, and 80.8 Watts. Average power output during the dual-task paradigm throughout sessions 1-6 were as follows: 76.1, 76.8, 75.3, 77.5, 80.2, and 80.1 Watts.

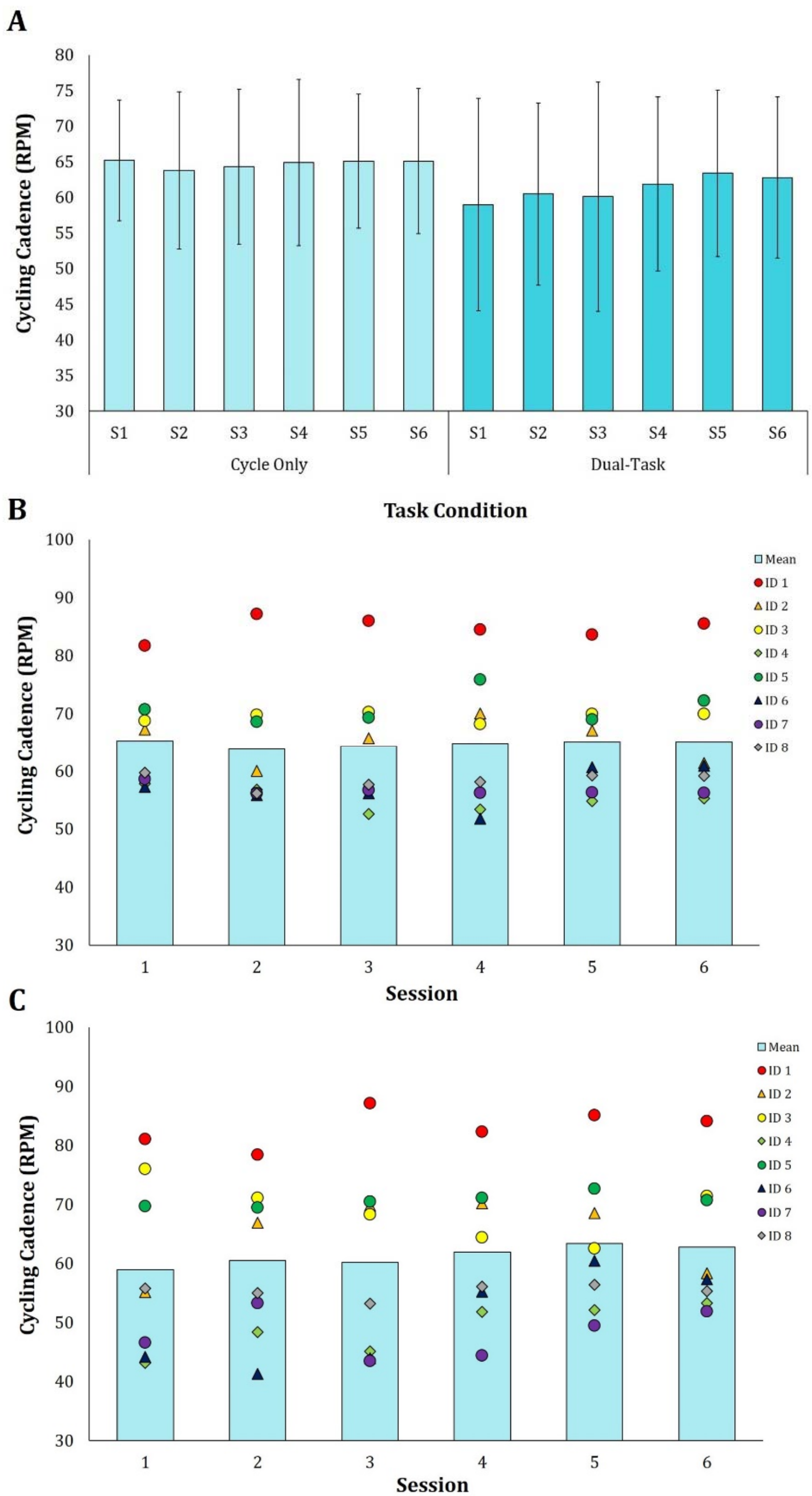


Figure 5.2: A) Mean cycling cadence (RPM) by task and by session; **B**) Mean cycling cadence for the Cycle Only condition, with individual performance across session visible; **C**) Mean cycling cadence for the Dual-Task condition of concurrent virtual navigation while cycling, with individual performance across sessions visible.

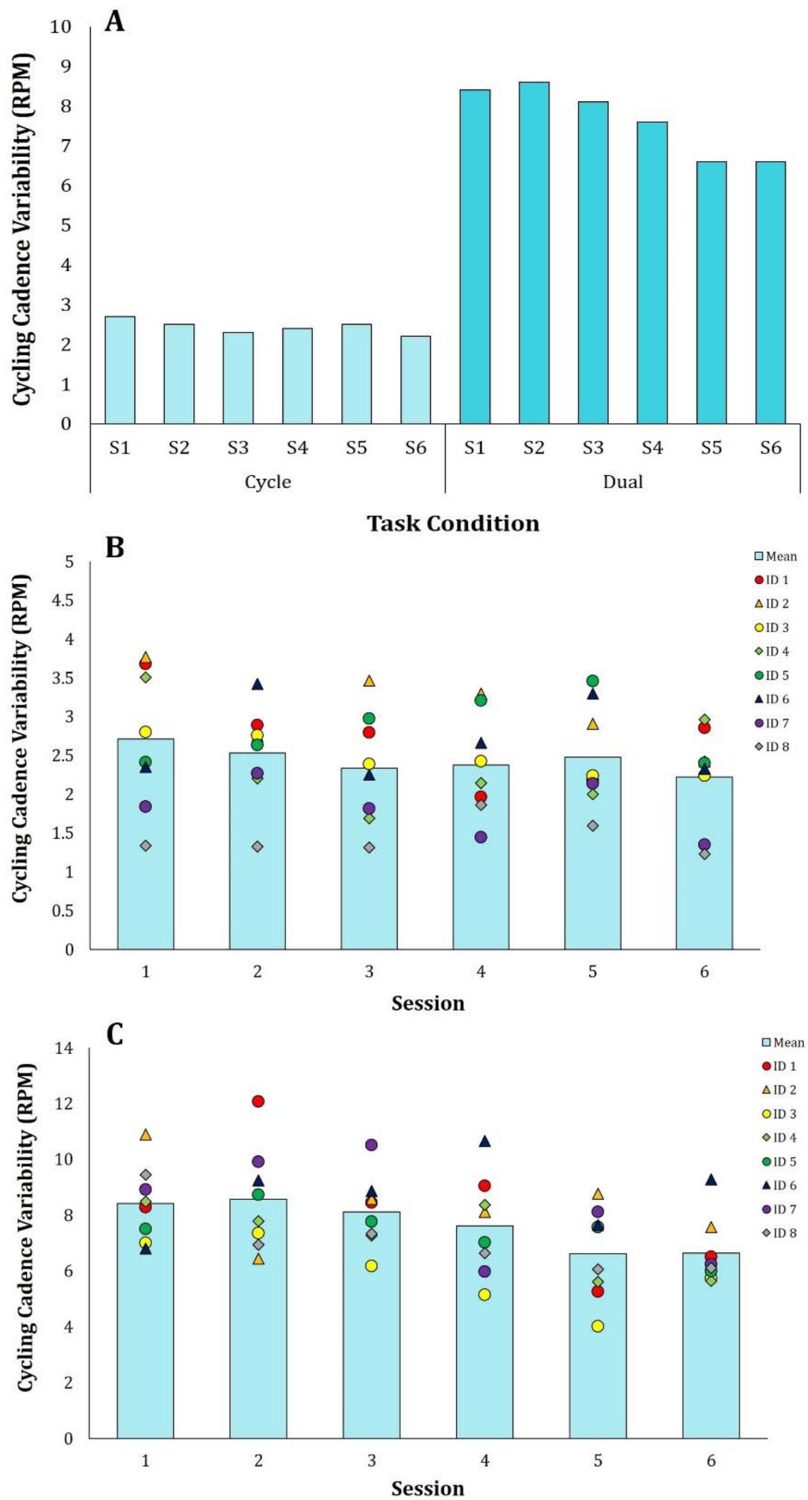


Figure 5.3: A) Average standard deviation values of mean cycling cadence (RPM) by task and by session; **B**) Mean cadence variability for the Cycle Only condition, with individual performance across sessions; **C**) Mean cadence variability for the Dual-Task condition, with individual performance across sessions.

A one-way ANOVA examining absolute heart rate, averaged over the entire duration of the exercise blocks, revealed a main effect of task ($F_{2,7}$ = 22.24(p = 0.0432)), with a Tukey's post hoc test revealing that heart rate during seated virtual navigation was significantly lower than heart rate during the two exercise tasks. There was no significant difference in heart rate between the cycling only and dual-task conditions (p = 0.55). A two way ANOVA revealed there was no main effect of session on heart rate ($F_{5,68}$ = 1.20(p = 0.42)), and no interaction effect between task and session with respect to heart rate ($F_{5,68}$ = 1.05(p = 0.48)). Mean heart rate values (bpm), when collapsed across sessions were 81.2 ± 11.7 for navigation only, 129.9 ± 10.3 for cycling only, and 124.4 ± 12.9 for the dual-task paradigm, as seen in Figure 5.4(A). Resting heart rate values were not different between sessions ($F_{5,7}$ = 0.98(p = 0.51)), with mean resting heart rate as 79.3 ± 11.1. Additionally, heart rate was expressed as a percentage of individual target heart rates, as determined by the VO_{2max} testing procedure. Comparisons were made between the cycling only and dual-task conditions. When heart rate was expressed this way, there was no main effect of task ($F_{7,68}$ = 0.05(p = 0.85)), no main effect of session ($F_{5,68}$ = 0.75(p = 0.62)),), and no interaction effect ($F_{5,68}$ = 1.02(p = 0.49)). This can be seen in Figure 5.4 (B).

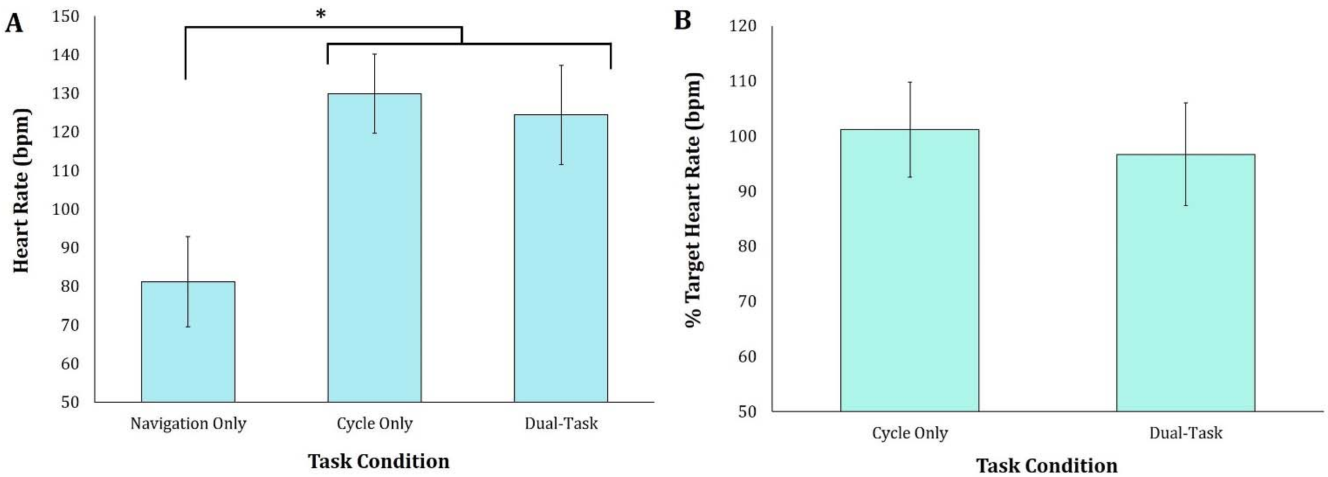


Figure 5.4: **A**) Mean (± sd) heart rate values over the 20 minutes of task performance of the three task conditions (expressed in absolute values); **B**) Mean (± sd) heart rate values over the 20 minutes of task performance of the three task conditions (expressed in values relative to the target heart rate as determined from the VO_{2max} test procedure).

Dual-task cost of cycling cadence (RPM) and power output (Watts) were calculated using the following equation: DT Cost = ([dual-task performance – single task performance] / single task performance)*100% (Falbo et al., 2016). One-way repeated measures ANOVAs revealed that there were no significant differences in dual-task cost for either average cadence ($F_{5,36} = 0.55$ ($p = 0.74$)) or for average power output ($F_{5,36} = 0.98$ ($p = 0.51$)) as a function of session. Dual-task cost for RPM throughout sessions 1-6 were the following: -10.6%, -5.4%, -7.6%, -4.4%, -3.0% and -3.8%. Dual-task cost for power output throughout sessions 1-6 were the following: -6.4%, -5.7%, -7.3%, -4.3%, +1.2%, and -0.2%.

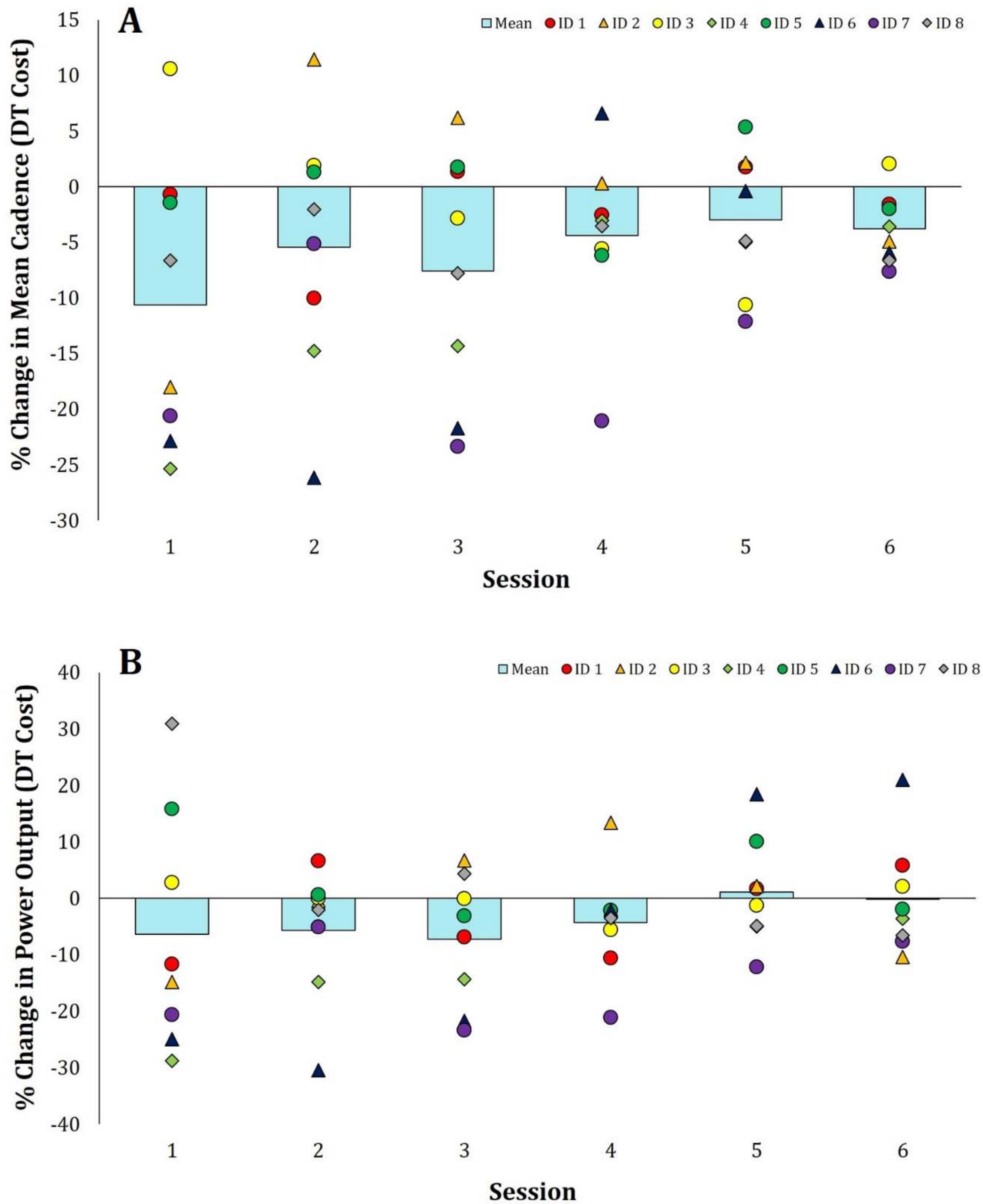


Figure 5.5: A) Dual-task cost, expressed as a percent change in mean cycling cadence for the concurrent exercise-executive challenge using virtual navigation; **B**) Dual-task cost, expressed as a percent change in mean power output (Watts) for the concurrent exercise-executive challenge using virtual navigation.

A one way repeated measures ANOVA on RPE data revealed that there was no effect of task (cycling only vs. dual-task) and no main effect of session on the average rate of perceived exertion throughout the exercise sessions ($F_{1,72}$ = 14.23 (p = 0.17)) and ($F_{5,72}$ = 0.39 (p = 0.84)) respectively. However, while not statistically significant, RPE for the dual-task condition was lower than the RPE for the cycling only condition, across all time points throughout the exercise period, suggesting that perceptions of exertion may differ depending on mental demand in addition to the physical demand of the exercise (see Figure 5.6).

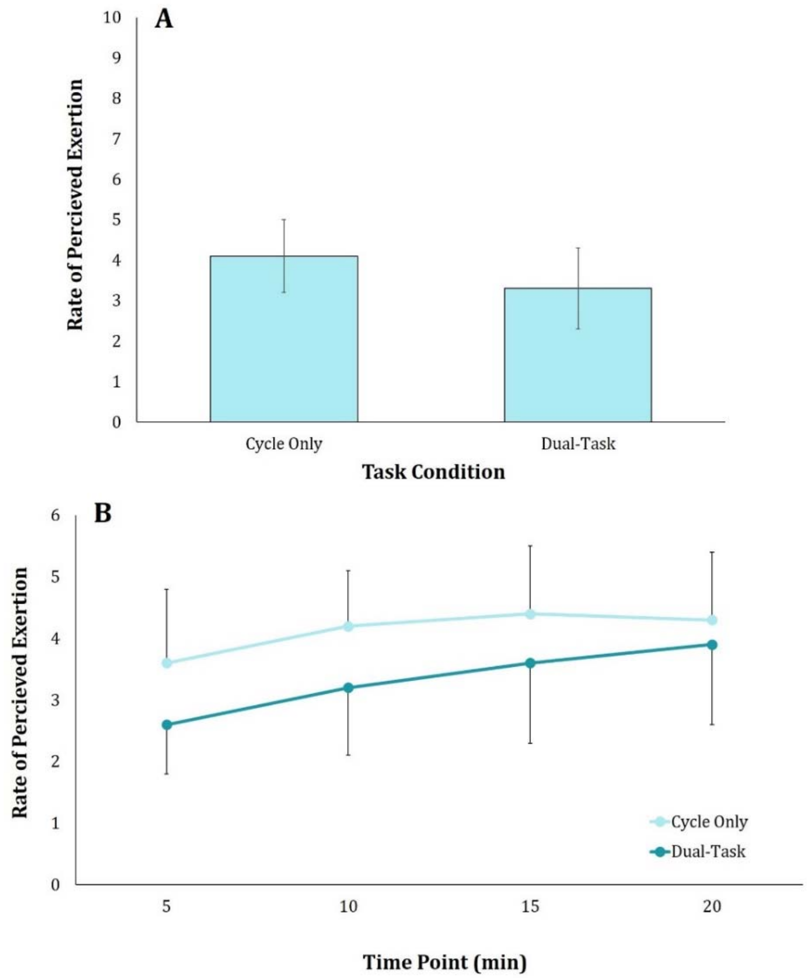


Figure 5.6: A) Average (+sd) RPE for the cycling only and dual-task conditions; **B**) Average (+sd) RPE at each of the four time points of measurement throughout the exercise tasks.

Navigation Task Performance Data

With respect to the effects of task, (navigation only vs. dual-task), there was no main effect for total distance covered ($F_{1,88} = 0.52$ ($p = 0.60$)). Means collapsed across sessions for the total distance covered across the navigation only blocks was 11.2 ± 0.8 km and for the dual-task blocks was 11.3 ± 0.6 km. There was no main effect for time moving forward ($F_{1,91} = 3.35$ ($p = 0.32$)) with mean forward motion times of 17.1 ± 1.8 min and 16.7 ± 1.3 min for the navigation only and dual-task conditions respectively. There was no main effect for dwell time ($F_{1,89}$ = 8.42 (p = 0.21)), with dwell times of 1.9 ± 2.1 min and 2.6 ± 1.5 min for the navigation and dual-task only conditions, respectively. Again, there was no main effect of task on total turn time (($F_{1,92}$ = 2.15 (p = 0.38)). Mean turn times were 3.24 ± 0.7 min and 3.28 ± 0.6 min for the navigation only and dual-task conditions respectively.

With respect to session order, there was no main effect for distance travelled ($F_{1,5}$(p = 0.84)). The average distance (km) travelled by session was 10.9, 11.1, 11.3, 11.4, 11.2 and 11.4 for sessions 1-6, respectively. There was no main effect of session order on the total time spent travelling in a forward motion ($F_{5,83}$ = 0.82 (p = 0.58)). The average time spent travelling forward, in minutes, by session was 16.4, 16.8, 16.7, 17.5, 16.8, and 17.3 for sessions 1-6, respectively. There was no main effect of session order on the dwell time (in minutes) ($F_{5,81}$ = 0.29 (p = 0.90)). The average dwell time in minutes, by session was 3.2, 2.3, 2.8, 1.9, 1.8, and 1.7 for sessions 1-6, respectively. Lastly, there was no main effect of session order on total turn time ($F_{5,84}$ = 0.71(p = 0.64)), such that the average turn time in minutes, by session order was 3.4, 3.4, 3.5, 3.0, 3.1, and 3.2 for sessions 1-6, respectively.

The design of the experiment, with the navigation task being cut off at 20 minutes regardless of whether or not the task was completed, lends itself to the issue of a ceiling effect of distance and time measures. Therefore, performance on the navigation task was additionally analyzed with respect to a navigation score of performance. Essentially, reaching a pin in the correct order of performance of the task was assigned a numerical value. If participants reached the pin they were assigned that value. If participants ended between pins, they were given half points. This scoring system can be seen in Appendix G. The maximal score a participant could receive is 42 points. One-way repeated measures ANOVAs were performed in order to examine main effects of task and session. There was no main effect of task condition (NAV vs. DUAL) on performance score ($F_{1,91} = 0.72$ ($p = 0.55$)) and no main effect of session on performance score ($F_{5,83} = 0.53$ ($p = 0.75$)). The mean (± sd) scores averaged across all sessions within each task were 38.6 ± 6.3 and 38.7 ± 5.7 for the navigation and dual-task conditions respectively. The mean (± sd) scores averaged across tasks within sessions were 33.8, 38.3, 37.3, 40.4, 40.9, and 40.9 for sessions 1-6, respectively. Lastly, there was no main effect on performance score between the different routes that were used within the experiment ($F_{5,}$ 83 = 2.57 ($p = 0.16$)).

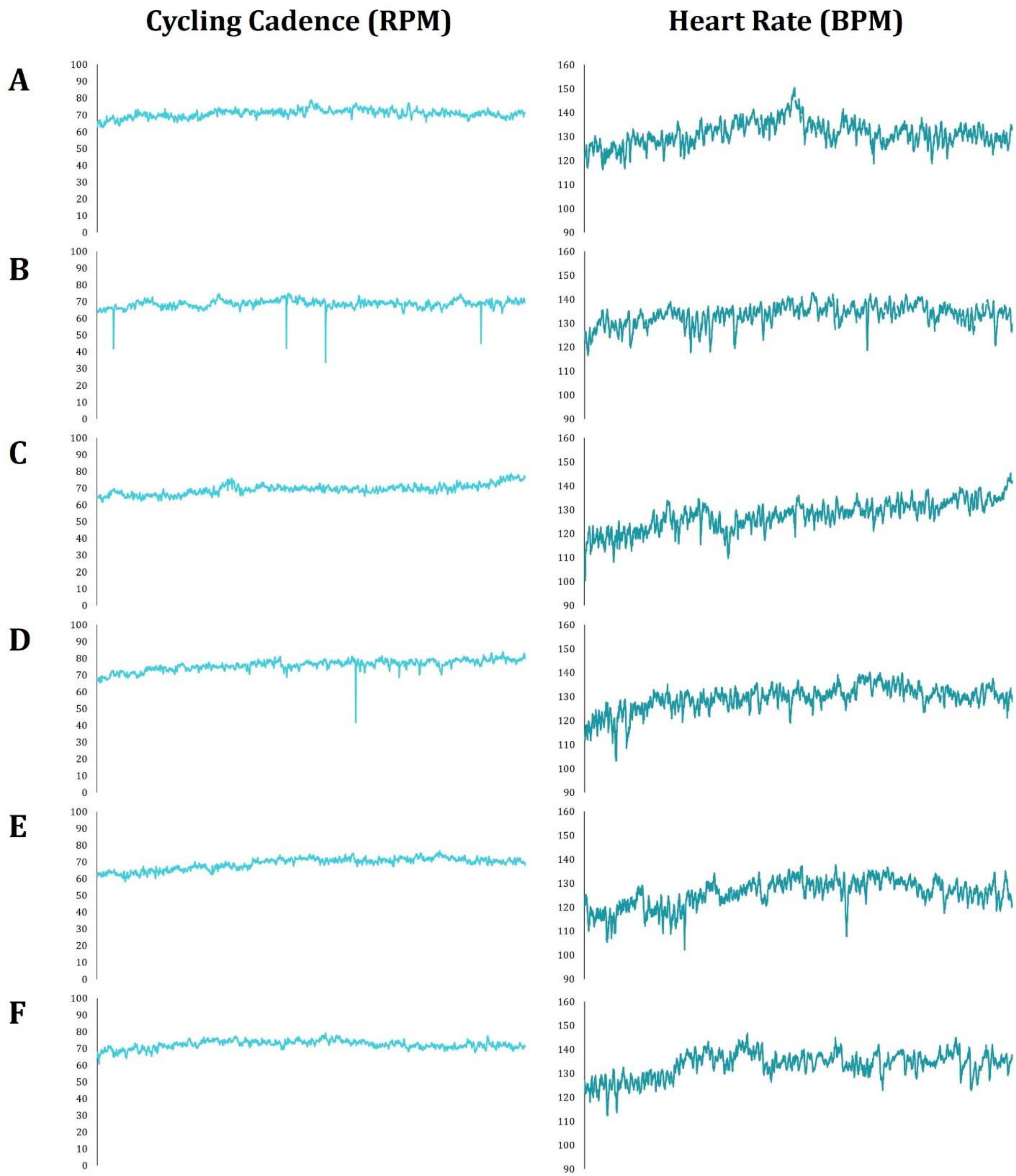


Figure 5.7: Participant ID 5 and their cycling cadence (RPM) and heart rate (bpm) across sessions 1(**A**) through 6 (**F**) for the Cycling Only task condition.

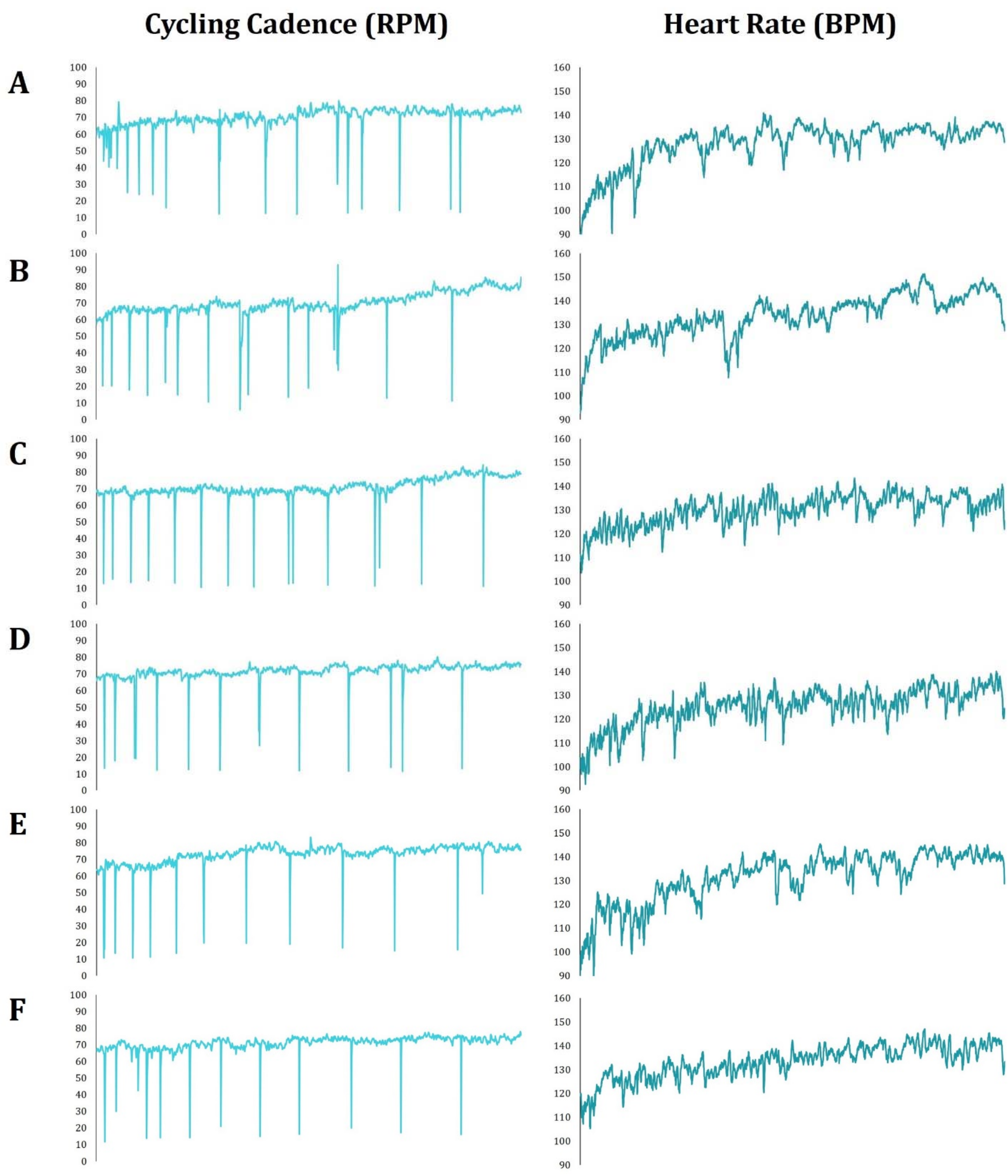


Figure 5.8: Participant ID 5 and their cycling cadence (RPM) and heart rate (bpm) across sessions 1(**A**) through 6 (**F**) for the Dual-Task condition.

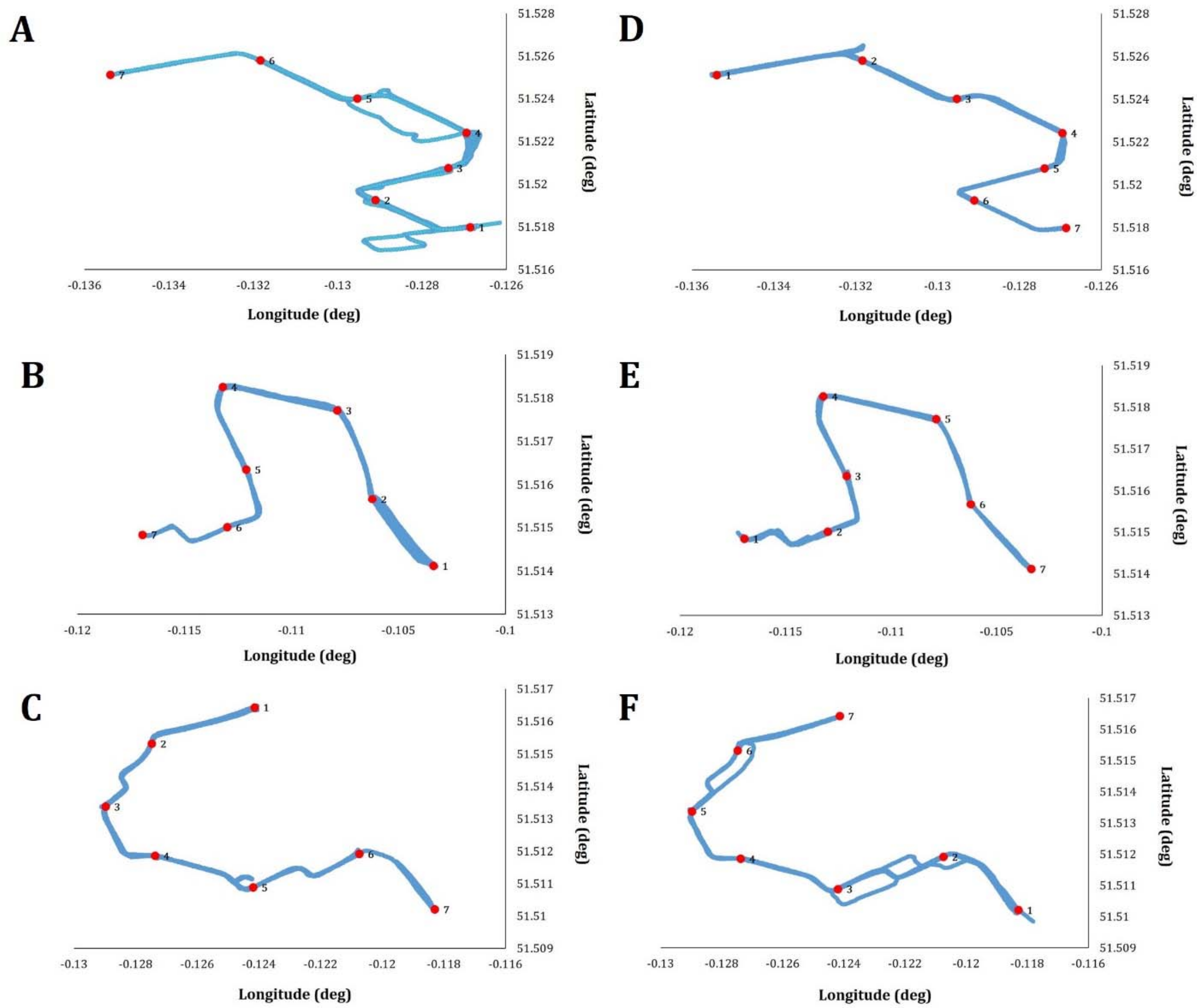


Figure 5.9: Participant ID 5 and their navigation performance (path travelled) across sessions 1(**A**) through 6 (**F**) for the Dual-Task condition. The red dots with numbers are the pins and associated pin numbers for the route that participants were tasked with finding.

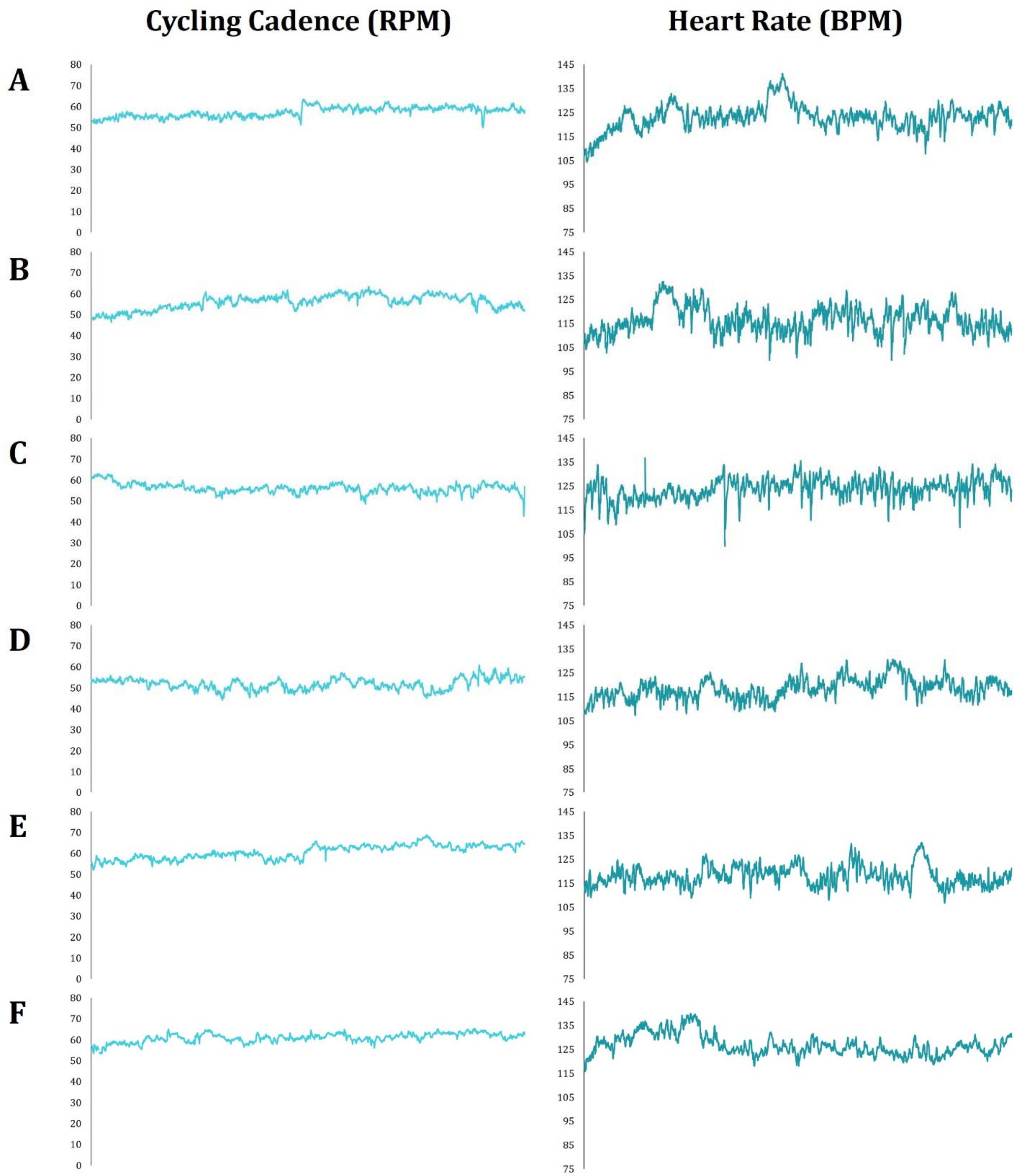


Figure 5.10: Participant ID 6 and their cycling cadence (RPM) and heart rate (bpm) across sessions 1(**A**) through 6 (**F**) for the Cycling Only task condition.

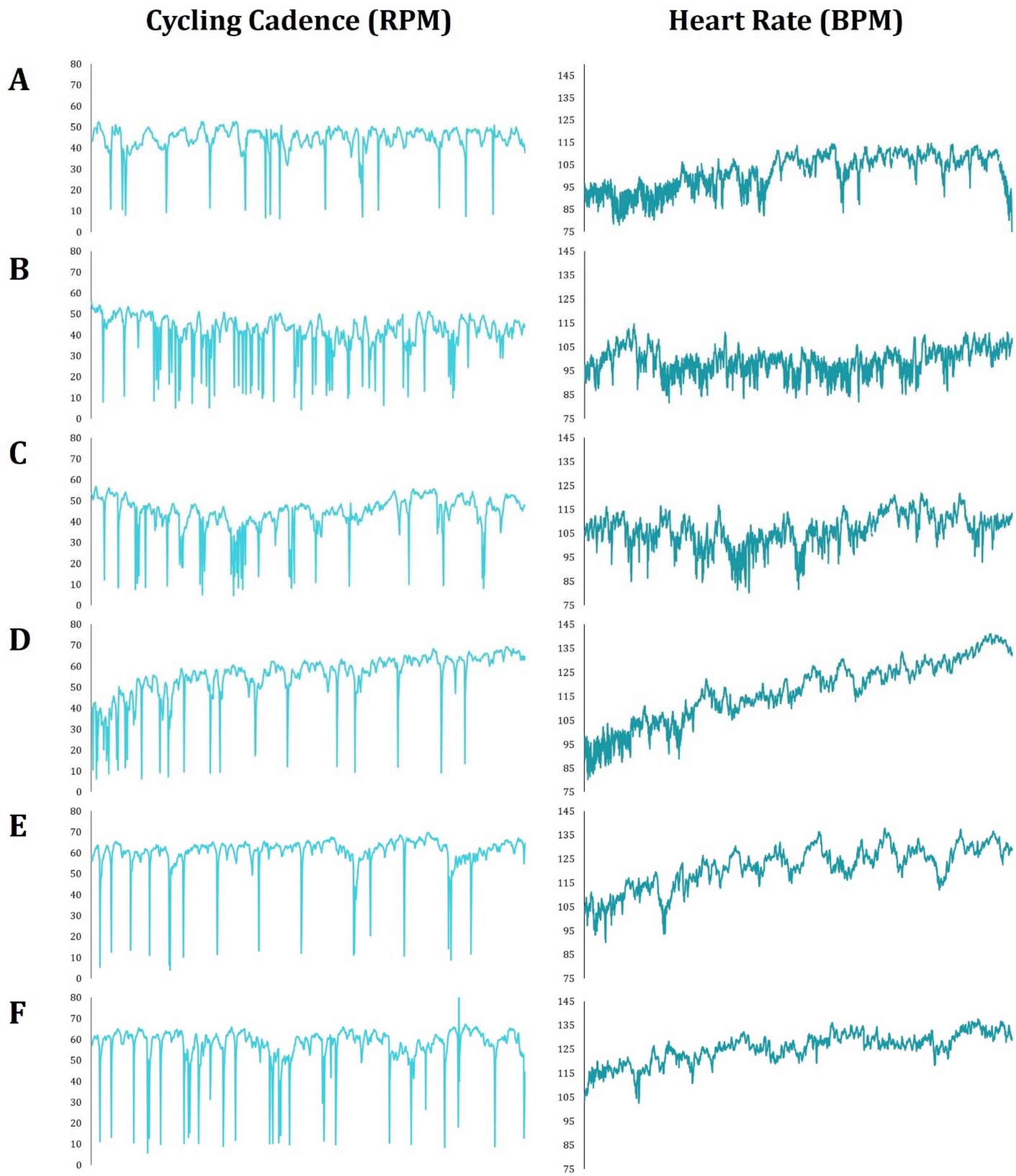


Figure 5.11: Participant ID 6 and their cycling cadence (RPM) and heart rate (bpm) across sessions 1(**A**) through 6 (**F**) for the Dual-Task condition.

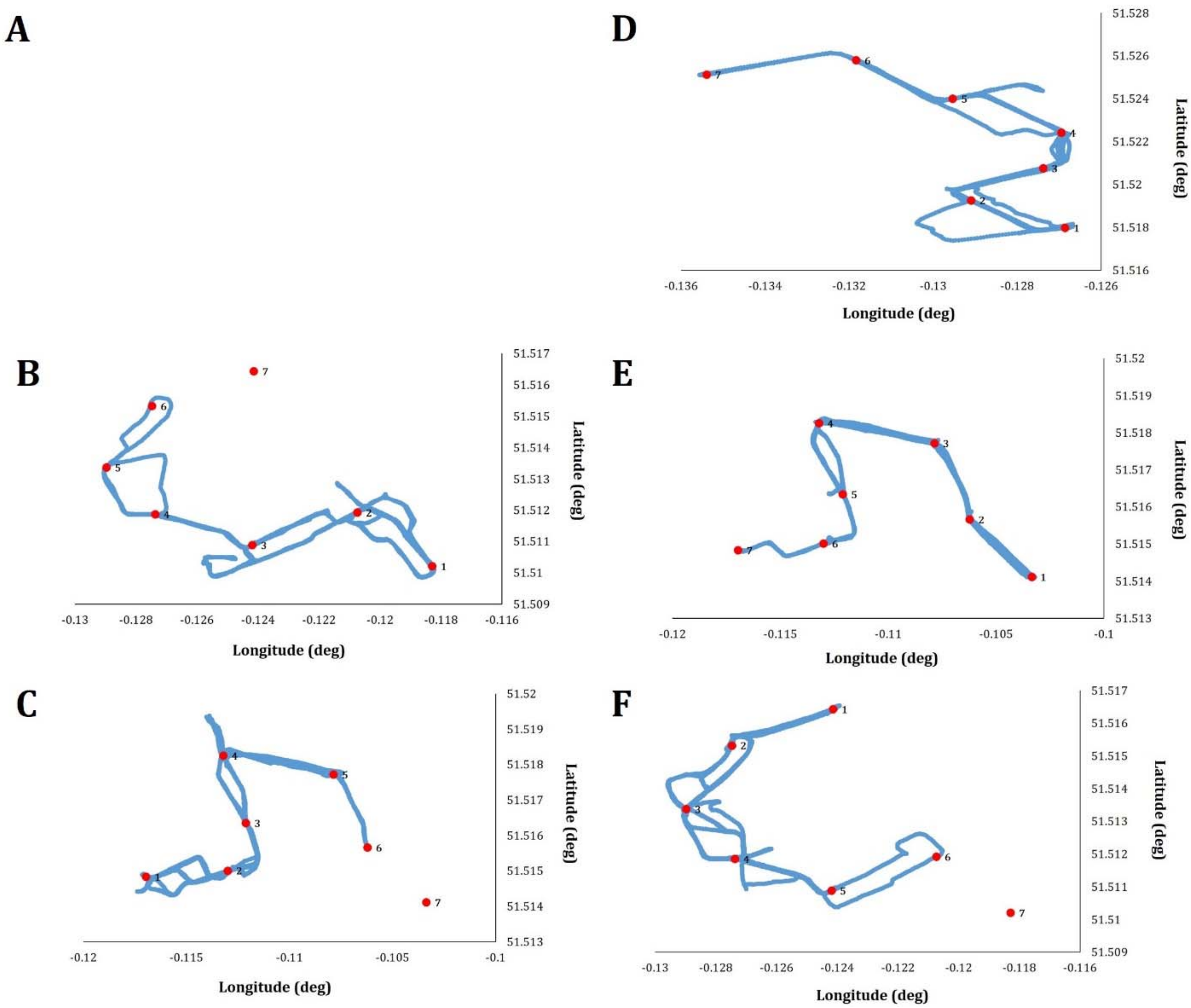


Figure 5.12: Participant ID 6 and their navigation performance (path travelled) across sessions 1(**A**) through 6 (**F**) for the Dual-Task condition. The red dots with numbers are the pins and associated pin numbers for the route that participants were tasked with finding.

Psychometric Data

With respect to psychometric data, results from the NASA Task Load Index revealed that there was no statistically significant difference in mental demand between the three tasks of navigation only, cycling only, or dual-task conditions (($F_{2,137} = 0.08$ ($p = 0.93$)) and that mental demand for these tasks did not change over time (($F_{5,131} = 1.11$ ($p = 0.46$)) as a factor of session. With respect to the physical domain of the NASA TLX, there was a main effect of task (($F_{2,138} = 63.11$ ($p = 0.016$)). Tukey's post hoc test revealed that the navigation only task was significantly less physically demanding that both the cycling only and the dual-task conditions. Interestingly, there is a trending significance for a difference in perceived physical effort between the cycling only and the dual-task, ($p = 0.0667$), indicating that cycling only was perceived as requiring more physical effort (see Figure 5.13 B). Physical perceptions of difficulty did not change over time, however, as there was no main effect of session (($F_{5,132} = 0.86$ ($p = 0.56$)). There was no statistically significant difference in perceived effort as a result of task (($F_{2,138} = 5.88$ ($p = 0.15$)) or as a result of session (($F_{5,132} = 0.88$($p = 0.56$)) indicating all tasks were considered effortful for all sessions. Total NASA TLX Scores (including mental, physical, temporal, effort, frustration and performance) were tabulated, and compared by task and by session in a separate analysis. Again, there was no significant effect of task (($F_{2,138} = 3.11$ ($p = 0.24$)) or of session (($F_{5,132} = 1.09$ ($p = 0.46$)) on the total NASA TLX Scores as seen in Figure 5.14.

Visual analog scale data were compared in a repeated measures ANOVA to examine for differences in perceived difficulty of navigation between the routes that were used. No differences in perceived difficulty were found as a factor of route layout (($F_{5,84} = 1.99$ ($p = 0.23$), suggesting that all routes were similar in perceived difficulty level.

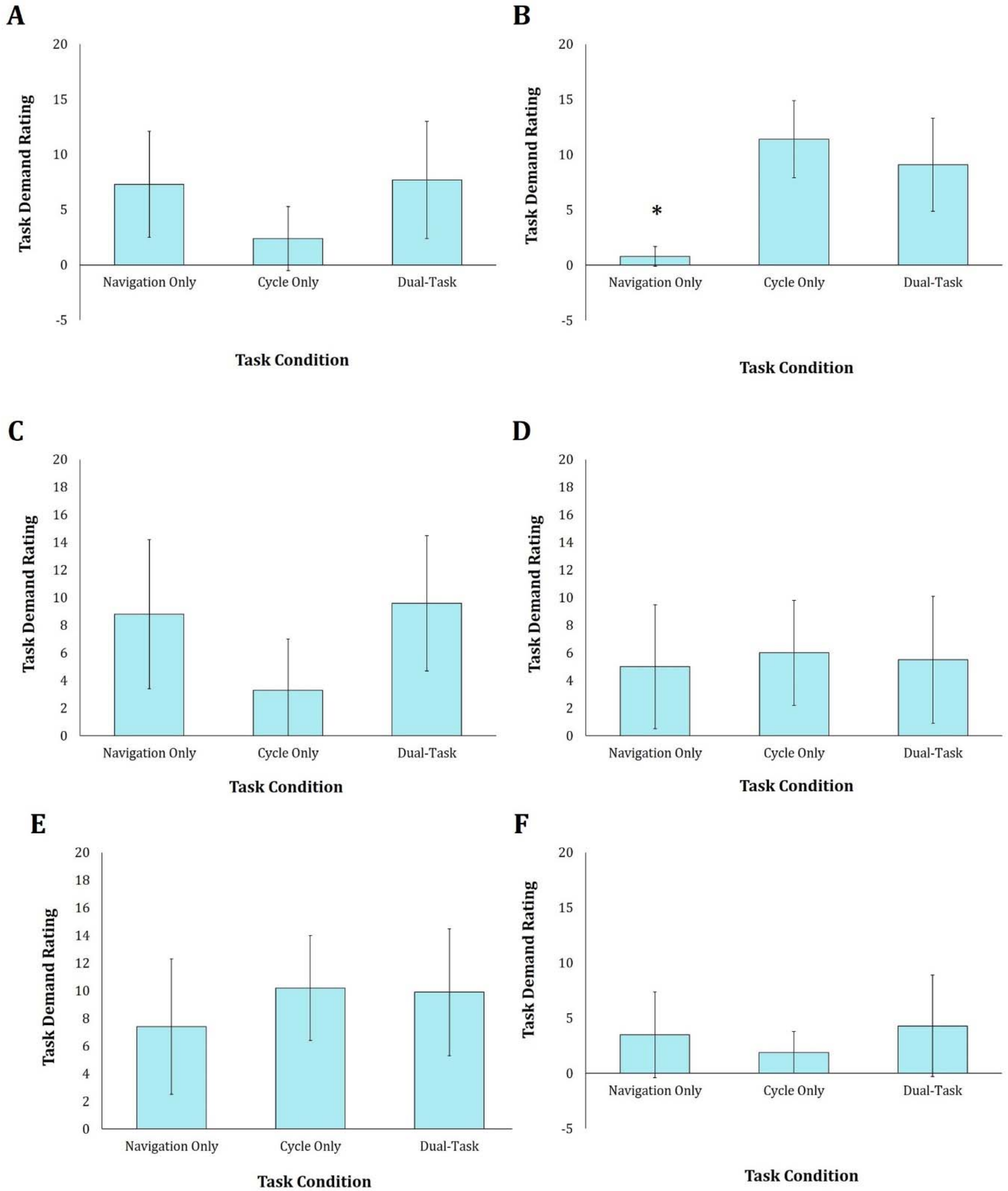


Figure 5.13: Average (± sd) NASA TLX scores across all sessions for each of the individual domains within the survey: **A**) Mental, **B**) Physical, **C**) Temporal, **D**) Performance, **E**) Effort, and **E**) Frustration. Note that for the Performance domain, a lower score indicates better perceived performance, while a higher score indicates poorer perceived performance; *$p < 0.05$.

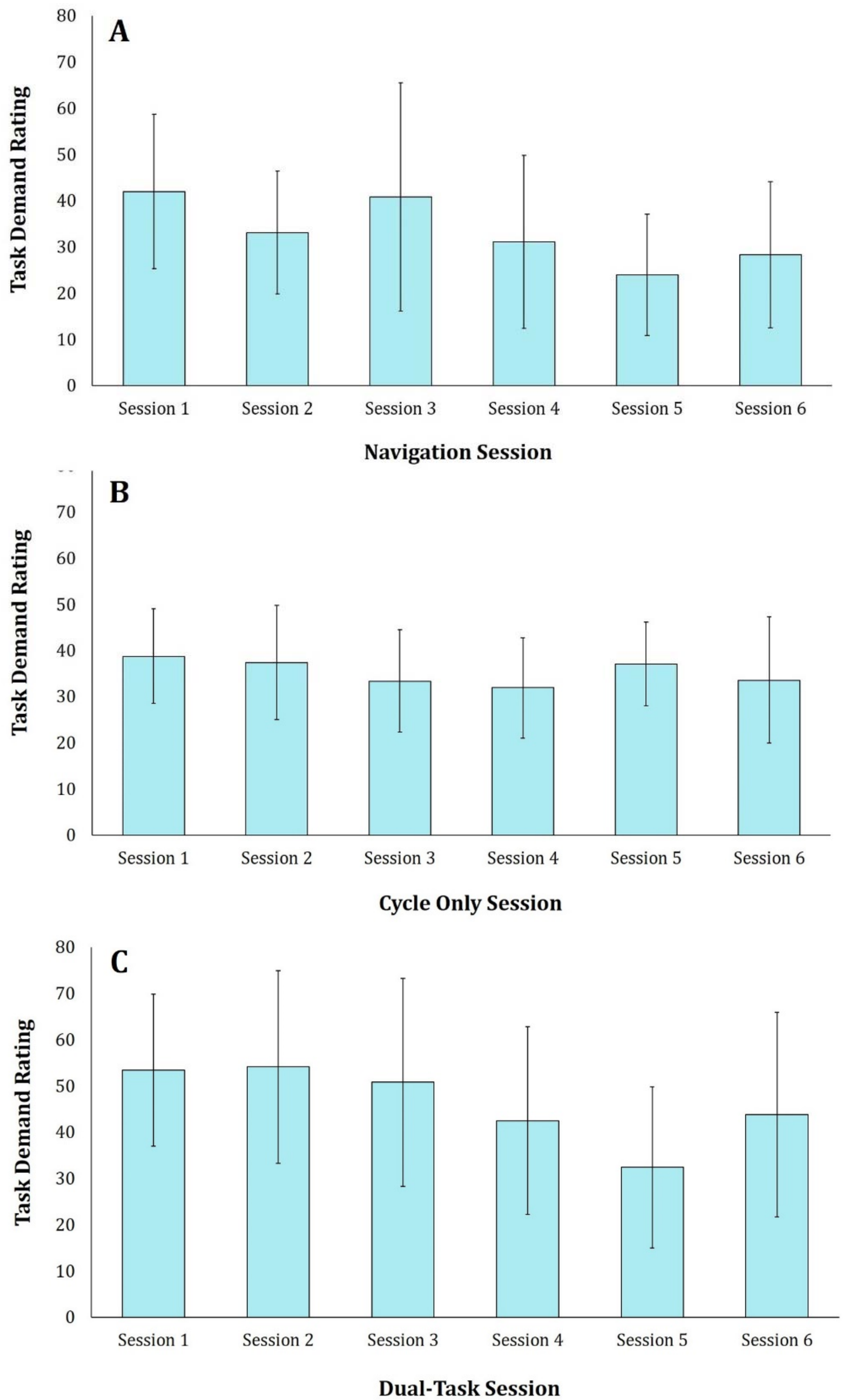


Figure 5.14: Average (± sd) NASA TLX Sum Scores (a sum of the scores from each of the six domains within the survey) by task and by session. **A**) Navigation Only task, **B**) Cycling Only task, and **C**) Dual-Task condition during which participants concurrently performed aerobic cycling exercise with the virtual navigation task.

5.7 Discussion

The overall objective of this work was to examine if dual-task trade-offs of a concurrent aerobic cycling and virtual navigation task were mitigated over repeated exposure to the task. This was examined through behavioural metrics of cycling cadence, power output, and navigation performance, physiological metrics of heart rate, and psychological metrics of perceived exertion and mental demand.

The hypotheses regarding differences in mean cycling cadence and cadence variability between the exercise only and dual-task conditions were not supported. This was true over the course of the six experimental sessions, but was also true for Session 1, the initial session when participants were exposed to the tasks. For Session 1, the mean cadences were 65.2 RPM for the cycling-only task and 59 RPM for the dual-task paradigm, while mean cadence variability values were 2.4 and 7.7 RPM for the cycling only and dual-task paradigms, respectively. This finding contrasts with prior research using this paradigm, as it was found that there was a significant difference in cycling cadence between the cycling only and dual-task conditions. However, in the previous study, (Study 3 of this thesis) participants only performed one task during each session, rather than all three tasks (navigation only, cycling only and the dual-task paradigm) all within one session. It is possible that there was better retention of task performance information while remaining within the experiment session.

As with previous work, the decrement in cadence and the increased cadence variability appears to be driven by the design of the task itself; the turn-a-round points cause most individuals to cease pedalling until they can turn themselves around within the virtual environment before continuing on. This was done to stay within the task instructions of not traversing through the buildings within the virtual environment provided within Google Earth. While participants were somewhat slower and more variable while performing the dual-task paradigm, no differences in power output or heart rate between the cycling only and dual-task conditions suggest that, while behaviourally different, it is likely that young healthy adults are able to achieve an aerobic workout from the concurrent exercise-executive challenge. The slower and more variable cadence during the dual-task paradigm was primarily driven by the turn-a-round points within the task itself, but that these moments were relatively transient within the overall time course of the dual-task duration.

The transient changes to cadence during this task design highlight the importance of considering virtual navigation task design and the resultant effects it may have to the behaviour of the exercise task. While numerous 180 degree turns were required of the individual, they were participating in a goal directed task by being required to find the pins (Moffat, 2009). Previous work showed that individuals pedal more slowly and more variably when they traverse through a virtual environment with no specific instruction. Therefore, navigation towards a goal or target location will be important for the task design in order to challenge executive function (Barcelos et al., 2015; Tait et al., 2017). Additionally, having a goal or a target for individuals to achieve will enable the researcher or clinician to effectively dose the challenge of the navigation task, by making the achievement of the goal more difficult. This could be achieved by increasing path length, number of turns, or features of the environment itself such as route layout and saliency of environmental stimuli (Barcelos et al., 2015; Wolbers & Hegarty, 2010).

Interestingly, within the Physical Domain of the NASA-TLX, there was a trending significant difference between cycling only and the concurrent exercise-executive challenge. Participants perceived as though they were physically working harder during the cycling only condition despite no significant differences in heart rate or power output between the tasks. The RPE data further supports this notion, as again, while not statistically different, RPE during the concurrent task challenge condition was lower than the RPEs reported during the cycling only condition, as both a grand average value as well as discrete time point values measured during exercise. No difference in VAS suggests that there were no differences in perceptions of difficulty between the routes, hopefully suggesting that all routes were demanding of executive function in a relatively equal manner.

Rate of perceived exertion is an assessment of self-perception *during* the task, while the NASA TLX is a self-reflection that is conducted once the task is *completed*. Both measures demonstrate that the exercise only task was perceived as more physically demanding, despite the results supporting no physiological differences in performance. This may be a result of the virtual navigation task providing a distraction from the negative perceptions of the exercise, such as discomfort and fatigue (Barcelos et al., 2015; Grealy et al., 1999). Regarding clinical practice, it may also be of importance to take into consideration the competitiveness of the individual. Some individuals were quite competitive, as they knew that they had multiple attempts to complete the virtual navigation task, and aimed to perform better each time. Virtual reality programs have the benefit of affording both individual and inter-individual competition and cooperation, which may lend itself to future work of a concurrent exercise-executive challenge undertaken within a group setting (Barcelos et al., 2015).

The experimental set-up of this study had a dissociation between cycling cadence and the speed at which the individual traversed through the environment. While this was an effective research tool – differences in navigation performance were solely due to individual navigation ability rather than differences in preferred cadence rate – this may be a limitation for future clinical implementation. Despite being informed of the independence between the two tasks, many participants continued to make short bursts of high RPM just after completing a turn to not "lose time" within the route. Additionally, when participants knew they were close to the timeline of 20 minutes but had the final ending pin within sight, they would begin to pedal faster in order to "win" or complete the task.

Differences in task performance and heart rate associated with the cadence rate can be seen between individuals in the Figures 5.9-5.14 below. Multiple strategies were adopted between the participants. For example, one individual with a high work rate (Watts) would at times choose to navigate around a building (i.e. move around another entire corner) and head back to their point of origin rather than cease pedalling to make a 180 degree turn. The participant said that they found this strategy physically easier, rather than ceasing pedalling only to have to start pushing against ~ 150 Watts starting from zero. While this strategy did not impact this participant's ability to successfully navigate in the virtual environment, strategies that adapt to the physical requirements of the exercise adopted by clinical populations may in turn, inadvertently, increase the executive load on the individual as well. This may be of important consideration for designing a virtual navigation task when considering how to appropriately dose the intensity of the executive task.

5.8 Conclusion

This study provides insight into the behavioural and physiologic metrics of a concurrent exercise-executive challenge over repeated exposure to the task. Specifically, the results from the study demonstrate that even within young healthy adults, there is substantial individual variability in performance of the dual-task challenge, but that differences appear to be mitigated to an extent over repeated exposure to the task. This in turn speaks to the objective of the thesis regarding titrating task difficulty within an individual, and also raises questions regarding the frequency at which the dosage of the executive demand is examined and modified. Having the appropriate dosing of both tasks will be vital for promoting adherence on the part of the individual, based on perceptions of physical and mental workload.

Chapter 6: General Discussion

6.1 Summary of Research Findings

The overarching objective of this thesis was to develop and evaluate a concurrent exercise-executive training paradigm, specifically by implementing a task that couples aerobic cycling with virtual navigation. This thesis began by examining the feasibility of coupling aerobic cycling with different executive tasks, including virtual navigation implemented with the freely available internet download Google Earth. Methodological approaches linked to understanding and controlling task challenge of both the exercise and the executive task were implemented to examine resultant effects on dual-task trade-off effects of the concurrent exercise-executive challenge. The rationale for this investigation came from the notion that while concurrent exercise-executive challenges have shown promising results with respect to improving executive function, 1) little to no investigation has occurred with respect to the physiological and behavioural parameters of the exercise itself, and 2) while great care is taken to dose the appropriate intensity of exercise, again little to no consideration is given to the dosing of the executive task itself. The promise of this line of inquiry is to advance approaches to develop a feasible and standardized approach to enhance brain benefits of aerobic and executive training, as well as maintain or improve cardiovascular capacity.

Behavioural metrics of concurrent exercise-executive challenge found that cycling cadence decreases and becomes more variable when the executive challenge is one of virtual navigation. As work rate, measured as power output is a function of cadence on aerobic exercise equipment (including cycle ergometers, treadmills and ellipticals), the individual work rate fluctuated as well. Interestingly, when aerobic cycling was coupled with an arguably more 'simplistic' executive task, the visual search task, mean cycling cadence increased and became less variable when compared to cycling by itself. This may have been because the visual search task does not have natural links to locomotor activity, and therefore there was less overlap of competing neural networks to allow greater dissociation of the tasks.

Physiological metrics of the exercise revealed that young healthy adults were able to maintain a cardiovascular work rate while performing a concurrent exercise-executive challenge. In Study 1, when participants performed various executive tasks (or no secondary executive task at all) while cycling, heart rate was on average at or above the target heart rate, but was generally lower and more variable during the navigation tasks. Studies 3 and 4 found that there was no difference in mean heart rate between cycling exercise alone and cycling exercise with the concurrent virtual navigation challenge.

Behavioural metrics of the virtual navigation task indicate that there were no differences in performance between completing the task by itself vs. completing the task concurrently with exercise. While not statistically significant, it does appear that there is an effect of presentation order. Therefore, if this concurrent exercise-executive paradigm were to be implemented in a rehabilitation or clinical setting, it may be beneficial to first expose the participant to the navigation only task for the first few sessions, prior to implementing the concurrent paradigm.

Psychological metrics found no major differences in mental workload, frustration or sum task load demand scores, as assessed through the NASA-TLX. There were no differences in perceived difficulty of the navigation task when it was performed by itself as compared to when it was performed concurrently with aerobic cycling, as assessed through a visual analog scale rating. Lastly, there were also no differences in rate of perceived exertion between aerobic cycling and the concurrent exercise-executive challenge, indicating that the dual-task paradigm did not increase the participants' sense of workload during the exercise. In fact, while not statistically significant, RPE values in Study 3 and Study 4 were lower during the concurrent exercise-executive challenge than they were for the cycling alone, despite no differences in heart rate or work rate as assessed through power output (Watts). This, along with participant feedback, suggests that the concurrent exercise-executive challenge provided a distraction away from the monotony, and the negative somatosensory feedback from the exercise.

6.2 Implications for Concurrent Exercise-Executive Prescription

Overall, the current series of studies in this thesis revealed the need for careful consideration of the design and implementation of the executive task used to couple with exercise, as the design of the task influences the behavioural performance of the exercise. The feasibility of concurrently coupling aerobic cycling with various executive tasks has been demonstrated in this thesis, but also has been confirmed in other studies with older adult participants, such as the studies conducted by Anderson-Hanley et al. (2012, 2014) and Barcelos et al. (2015). Novel to this thesis was the approach of using a freely available internet platform in the form of Google Earth, which has numerous benefits for implementation. First and foremost is the ability of the researcher / therapist to control, and therefore dose, the demand of the navigation task. Google Earth is a relatively simplistic software tool, and difficulty of software of programming knowledge has been cited as a barrier to implementation and dosage of executive demands by others (Levac, et al., 2017). Google Earth has the additional benefit of using real-world cities for navigation, and as this software is likely only to improve with time, the potential to have those in-patient populations virtually navigate within their own city or neighbourhood may be possible. This will hopefully enable greater transfer to ADLs and independent living after a neuro-traumatic injury (Kelly et al., 2014; Tait et al., 2017). Lastly is the ease of implementation of the concurrent exercise-executive task challenge using this paradigm. Google Earth is a free download available through the internet, making it available to a wide array of clinical and home settings and minimal costs, as other software programs are more expensive and may require programming expertise as previously mentioned (Levac, et al., 2017).

As the concurrent exercise-executive challenge of virtual navigation using Google Earth was feasible, this led to the examination of task and individual factors likely to impact performance of virtual navigation. Understanding factors related to performance on an executive task one wishes to couple with exercise is important for appropriately dosing the intensity of the executive task. It was hypothesized that both the city layout (grid vs. no-grid) and route length (short vs. long) would impact virtual navigation performance, as evidenced by other research (Lövdén et al., 2007). It was further hypothesized that prior videogame play and navigational experience would also impact virtual navigation performance (Momi et al., 2018). However, neither were the case for the particular navigation task design used in this thesis. Both findings are somewhat contrary to prior research. Lövdén et al. (2007) revealed that while men outperformed women on a virtual navigation task within grid-like environments, this advantage disappeared in the non-grid like environments. This may suggest that a non-grid like environment design in a virtual navigaiton task is a more beneficial tool to use so as to challenge execuitve function somewhat equally between the sexes. In the case of Lövdén et al. (2007), this difference was examined on the basis of sex. This thesis did not find a main effect of sex on virtual navigaiton performance with the specific task designed used; rather it revealed a large variability in individual performance that may be attributable to a multitude of individual and task factors, as well as possible interactions between them that were not examined in this work. Wolbers & Hegarty (2010) discuss numerous factors that are likely to influence our navigational ability, including visuospatial skills and differences in executive function, use of environmental and self-motion cues, and representations of egocentric and allocentric navigation strategies both used in real time and from memory. The vast array of factors contributing to individual variability in performance further demonstrates the need to not only control for the dosage of the exercise (in order to attain cardiovascular benefits) but also the dosage of a virtual navigation task coupled with the exercise so that it is at an appropriate intensity.

While virtual navigation performance was not affected by performing it alone vs. concurrently with exercise, the design of the virtual navigation task used did affect the behavioural performance of the exercise itself. Participants in this study did show a decrement in mean cycling cadence when performing the concurrent exercise-executive challenge compared to an exercise challenge alone. The decrement in cadence was highly driven by the demands of the navigation task; participants were required to make numerous direction reversals by completing a 180 degree turn, ideally without traversing through the surrounding buildings (as per the task instructions, since this is a feature that is allowed in Google Earth). Furthermore, it is apparent that at first exposure to the concurrent task challenge there is a large degree of individual variability. After repeated exposure to the dual-task paradigm, the differences in individual variability decreased, suggesting an adaptation effect over time. During chronic exercise training, individuals are regularly assessed with regard to their aerobic capacity, as participation in aerobic exercise leads to improvements in aerobic capacity (Wilson et al., 2016). Regular assessment of aerobic capacity enables the researcher or therapist / trainer to adjust exercise work rates to ensure that the individual is still working at the desired intensity (Wilson et al., 2016). Other research that examines performance on executive tasks must deal with the issue of adaptation or learning; changes in performance to tasks (Stroop Task, Flanker Task, Trails A & B etc.) may very well be due to retained information regarding the task or retaining of task strategies. In these cases, the adaptation to the executive task is considered a possible limitation of the research, and great care is taken in study design to mitigate this influence as best as possible. However, if we understand that individuals are likely to improve at a task they perform repeatedly, it raises the issue of importance for not only reassessing and dosing the exercise task, but also reassessing and dosing the executive task as well. Taken together, these studies again address the need to carefully dose the intensity of the secondary executive task, and also raise the question of whether or not scientific research should think about dosing the individual components of exercise and executive challenge separately, or if we need to consider them together as a different task in and of itself that needs to be examined for appropriate dosage.

The behavioural changes to the cycling cadence that were observed in this thesis were highly dependent on the design of the virtual navigation task that was used to couple with aerobic cycling. The design of having participants move from Pin N to Pin N+1 and back in sequential order was used in order to 1) allow participants to sequentially build a visuospatial map of the virtual space without over taxing working memory, and 2) to promote an increased time between turn-around points which were to help either maintain heart rate at the target value or to allow it time to increase towards the target value. This appeared to be an effective approach, as it provided participants with an opportunity to adapt to the dual-task paradigm in the first few minutes of the exercise bout, without compromising the purpose of an aerobic workout. For a concurrent exercise-executive challenge to be implemented in clinical practice, it will be important to consider the design of the virtual navigation task itself, to ensure that the level of executive challenge is matched to the cognitive capacity of the individual performing the task. Aspects that need to be considered during the design of a virtual navigation task may include the layout of the city, although this was not found to be a factor in Study 2 with young healthy adults. Based on feedback from participants, the main factor for consideration is the distance between markers that are used to indicate the path that participants are required to determine in order to move throughout the environment. Participants preferred if the route marker for marker N+1 was visible from marker N, or if marker N+1 was visible almost immediately after traversing past marker N. An additional factor that was noted was the width of the roadways within the environment. Narrow alleyways were difficult to traverse in this participant group. Additionally, it will also be important to consider the visibility and saliency of the marker within the virtual environment and how well it contrasts with its surroundings. This did not appear to be an issue with young healthy adults, but older adults, or those with declining vision may require a different marker design or size in order to correctly distinguish it from the virtual surroundings.

The number of turns that an individual is required to make will also be an important factor in the design of a virtual navigation task to couple with exercise, as individuals tend to slow or cease pedalling for transient periods based on the task instruction of turning around and returning to a previous destination. If there are multiple turn-around markers, this may lead to an overall decrement in cycling cadence, and subsequent heart rate values, thus negating the cardiovascular benefits of the exercise.

6.3 Navigation as an Executive Training Task

Human spatial navigation is predominately supported by the hippocampus and specialized neurons in the hippocampus and entorhinal cortex to encode for relationships between movement and spatial location within an environment (Moser et al., 2015). It is this natural link between the functions of spatial navigation and rhythmic, locomotor activity that may be best exploited during a concurrent exercise-executive task challenge design in order to mitigate potential dual-task trade-offs. Since the task of spatial navigation has such strong links to locomotion, there may be less of a dual-task trade-off compared to using other executive or cognitive training tasks, and would hopefully enable individuals to better maintain a cardiovascular workload.

Of course, it is possible to couple 'traditional' executive and cognitive training tasks with exercise. The first study in this thesis combined a visual search task with aerobic cycling. Beyer et al. (2017) had participants perform a modified Flanker task using lateral arm movements while performing stationary aerobic cycling. The concern of coupling a traditional executive task with exercise is the likelihood that any improvements to executive function will be highly specific to the domain that was trained. The literature supports the notion of task specificity: improvements to executive function tend to only appear for the executive function that was trained, with minimal to no transfer effects to other executive domains, or to activities of daily living (Kelly et al., 2014; Marusic et al., 2018). That said, if the goal of a rehabilitation protocol for a specific individual is to improve a specific function (e.g. response inhibition), then it may be more beneficial to couple a traditional inhibitory executive task with exercise ensuring that aerobic benefits are being achieved through achieving the appropriate intensity of exercise. However, having individuals engage in a spatial navigation task may help to alleviate the concern of near versus far transfer effects and transfer to activities of daily living, as navigation requires a multitude of executive demands, including: attention, working memory, visuospatial working memory, decision making and planning (Kelly et al., 2014; Tait et al., 2017).

A virtual navigation task would be dependent on hippocampal function, with possibly more transient reliance on or requirement of executive function. The broader network supporting spatial navigation includes the parahippocampal place area which is activated by presence of navigation related structures such as buildings and streets, the retrosplenial cortex which enables humans to orient themselves within a larger environment, and the occipital place area which is activated (Epstein et al., 2017). Likely, the executive demands of a navigation task are more predominately used at decision points such as turns or changes in direction. Familiarity of the environment and the complexity of the environment may also impact the executive demands. However, navigation abilities have been shown to decline with age, along with atrophy of the hippocampus *and* the frontal cortex (Erikson et al., 2011; Moffatt, 2009). Erikson et al. (2011) demonstrated that an aerobic walking program in healthy older adults was able to ameliorate hippocampal volume loss and even help to increase hippocampal volumes while also showing improvements to spatial memory performance. Maguire et al. (2000) have increases to the volume of the anterior hippocampi of taxi drivers in London, England after undergoing training referred to as “The Knowledge”, a process that takes an average of 2-4 years to complete. If aerobic walking improves spatial memory and impacts hippocampal plasticity (Erikson et al., 2011) and spatial navigation training promotes hippocampal plasticity (Maguire et al., 2000) then it may be plausible that virtual navigation as a training tool not only has the potential to maintain or improve multiple executive functions and ADLs, it may also help to preserve the connections between the hippocampus and frontal cortical areas to continue to support human spatial navigational ability (Barcelos et al., 2015).

6.4 Biological Significance of Coupling Navigation with Movement

This thesis proposed the use of virtual navigation as the executive task to couple with aerobic exercise. Virtual navigation is an executively demanding task that requires the use of multiple executive and cognitive domains, thus potentially promoting improvements to numerous executive functions and activities of daily living (ADLs) (Wolbers & Hegarty, 2010; Wolbers & Wiener, 2014) Navigation has natural links to locomotor activity, as evidenced by overlap of brain networks that are activated upon navigation and motor control (Bender et al., 2015; Korotkova et al., 2018). Lastly, altering the demand of a navigation task can be done in many ways: city used, route length, route layout, use of landmarks, visibility of landmarks, and the general instructions of the task itself.

Navigation studies in both humans and rodents have shown an increase of power within the electrophysiological theta rhythm of approximately 4-8 Hz (Kaplan et al., 2012). Theta power has been shown to increase upon movement initiation, as well as in human studies using virtual environments when the environment is familiar (Kaplan et al., 2012). Of particular interest is hippocampal theta rhythm, as these oscillations have been associated with hippocampal place cell activity during exploration tasks (Shin & Jadhav, 2016). Multiple direct and indirect connections between the hippocampus and the PFC have been identified which are believed to enable coordinated activity between these areas, and thus directly impact behaviour (Shin & Jadhav, 2016). A review by Shin & Jadhav (2016) suggests that theta oscillations become more synchronized in nature between hippocampal regions and the PFC during "periods of memory guided decision making as compared to passive exploration" (pg. 163), and that this synchronization may in turn be important for supporting cognitive and executive functions.

In addition to its importance in spatial processing, research regarding hippocampal theta rhythms also focuses on its relation to locomotor activity. Input to the hippocampus regarding locomotion is vital for updating spatial location within an environment to ultimately decide where or what to move towards (Bender et al., 2015; Korotkova et al., 2018). Research using intracranial electrodes has found that both the frequency and amplitude of field potential frequencies of hippocampal theta rhythm are proportional to locomotor speed, and that neuronal firing rates within the hippocampal and parahippocampal formation also scale with locomotor speed, thus revealing a link of hippocampal theta rhythm to the control of locomotion (Bender et al., 2015; Korotkova et al., 2018). Taken together, a concurrent exercise-executive task challenge using rhythmical locomotor activity with a virtual navigation platform, one may be able to take advantage of this inherent system to further promote neuroplastic change within the brain, within regions that are important for executive and cognitive functions.

The concurrent task challenge of virtual navigation and exercise may also have important biological significance with regards to not only physical health, but to mental health as well. Anxiety and depression are among the most common mental health disorders, with high risks of developing other comorbidities while also placing a substantial strain on the health care system (Bartley et al., 2013; Schuch et al., 2016). Exercise has been implemented in both individual and adjunctive manners to examine effects on anxiety and depression (Bartley et al., 2013). While the literature has produced somewhat conflicting results, there is a general trend for positive effects of exercise participation to anxiety and depression disorders (Bartley et al., 2013; Schuch et al., 2016).

Research has also demonstrated the importance of greenspace and natural scenery as a contributing factor to overall human health. Research examining the coupling of aerobic exercise with virtual navigation have used different game software in order to implement a navigation task, in different environments. The current graphics of Google Earth afford the design of a navigation task through densely populated urban environments, but not nature settings. There is evidence supporting the importance of exposure to nature, whether in natural environments or computer generated virtual reality, as nature exposure has positive effects on measures of cognitive and executive function, decrements in cognitive fatigue and physiological stress, and improvements to overall mood (Valtchanov & Ellard, 2010; Valtchanov et al., 2010). Virtual reality scenes of nature environments may be of great benefit for those with disordered movement, who are unable or unwilling to travel outside the home unassisted. Virtual reality may further promote benefits to executive function and mental health for those living in colder climates, who may feel less comfortable partaking in outdoor activity during winter months when walkways are covered in snow and ice, increasing the fall risk or perceived fall risk to the individual.

6.5 Limitations and Future Research

This thesis provided insight into the dual-task trade-offs that occurred in healthy young adults as a means for informing task design considerations prior to implementation within older adult and patient populations. To examine the possible differences in dual-task trade-offs with the concurrent exercise-executive challenge, it will be important to conduct similar research within different populations before we have a clear picture of what task demands need to be considered when designing a virtual navigation task.

To address priorities for potential translation to clinic use and discussion of standardization, future research will be required to continue to examine the broader categories of 1) the modality with which virtual navigation is coupled and, 2) the control challenges imposed by the secondary task. This thesis examined the dual-task trade-offs that occurred while coupling aerobic cycling with virtual navigation, and therefore the physiological and behavioural metrics that were observed here may not necessarily translate to other types of exercise equipment, such as treadmills, elliptical machines or recumbent steppers. The use of the recumbent bike was to provide support to the torso while freeing up the hands to control the virtual navigation task. This exercise mode has been commonly used for individuals with mobility restrictions (Tang et al., 2009).

The control of navigation in such stationary exercise modalities (stationary cycling, treadmill walking) requires further consideration to ensure intuitive control and to minimize challenges that may be associated with the coupling of the two tasks. This thesis proposed the use of Google Earth as it is a free program available for download to anyone with an internet connection, making it widely available to clinicians and researchers. This thesis also implemented a navigation task whereby individuals progressively constructed the route that they were asked to follow by connecting pins placed along the route of interest. There are numerous ways in which the design of the secondary executive task could influence individual performance, and how it couples with exercise. For example, the pins could be placed farther apart, making the route more difficult to create and / or the route could be longer, requiring individuals to find and remember the location of more pins. Conversely, an entirely different approach could be used altogether. Individuals could be shown a topographical map of pin locations prior to being placed in the first-person view within the virtual environment. Participants could be asked to find specific landmarks or buildings within an environment, rather than using pins as a way to mark their place within the environment. Lastly, the parameters of task performance of both the exercise and the secondary task likely also differ as function of the software used to create the virtual environment. Therefore how these findings translate to software and games outside of Google Earth is unknown.

The coupling of the virtual navigation task and the aerobic cycling were independent in this study, in that the velocity in which the participant moved through the virtual environment was independent of cadence rate. Future work should examine how cadence and resultant heart rate change as a factor of having virtual movement coupled to the cadence at which the individual is cycling at on the bike. Specific to the current approach, some individuals may find using a joystick difficult, due to unfamiliarity and the potential loss of fine motor control within the hands (e.g. stroke patients). More generally consideration of the coupling between the control of Fitting the front of the bike with a large steering wheel to make the task more akin to driving, or enabling the front end of the bike to turn (in a similar fashion to riding a bicycle outside) may be beneficial for patient populations as it mimics movements that they are more familiar with, does not require the fine motor control like the joystick, and may serve to create a feel of a more immersive environment.

Additionally, as research in this field continues, researchers and clinicians will have to discuss the components of interest or concern for the ability to develop a standardized protocol for a training regime. Individual variability, with respect to fitness level, executive and cognitive capacity, familiarity with virtual navigation software or games, and navigation ability are likely all factors that will need to be considered and addressed. This leads to further questions about which questionnaires and / or assessment methods and measures will be most informative for designing a rehabilitation protocol coupling aerobic exercise with virtual navigation.

6.6 Conclusions

The studies in this thesis highlight the methodological considerations that must go into designing a concurrent exercise-executive challenge, specific to using virtual navigation as an executive task. This thesis also highlights the importance of considering not only the importance of dosing the task challenge for the exercise portion of a concurrent paradigm, but the dosing of the difficulty of the executive task that is coupled with it. Progression of both the exercise and executive task parameters will be important for continuing to challenge both the cardiovascular and cognitive systems. Lastly, this thesis also addresses that research examining the beneficial effects that may occur to executive function and cognition as a result of a concurrent paradigms also examine the potential behavioural and physiological changes that may occur to the exercise task itself in future research. Dual-task paradigms need to examine trade-offs to both tasks in order to provide a clearer understanding of performance, as well as to maintain the goals of rehabilitation.

References:

Abernethy, B. (1988). Dual-task methodology and motor skills research: some applications and methodological constraints. *Journal of Human Movement Studies*, *14*, 101–132.

Allen, P. A., Lien, M. C., Ruthruff, E., & Voss, A. (2014). Multitasking and aging: Do older adults benefit from performing a highly practiced task? *Experimental Aging Research*, *40*(3), 280–307. https://doi.org/10.1080/0361073X.2014.896663

Anderson-Hanley, C., Arciero, P. J., Barcelos, N., Nimon, J., Rocha, T., Thurin, M., & Maloney, M. (2014). Executive function and self-regulated exergaming adherence among older adults. *Frontiers in Human Neuroscience*, *8*(December), 1–8. https://doi.org/10.3389/fnhum.2014.00989

Anderson-Hanley, C., Arciero, P. J., Brickman, A. M., Nimon, J. P., Okuma, N., Westen, S. C., Merz, M.E., Pence, B.D., Woods, J.A., Kramer, A.F., & Zimmerman, E. A. (2012). Exergaming and older adult cognition: A cluster randomized clinical trial. *American Journal of Preventive Medicine*, *42*(2), 109–119. https://doi.org/10.1016/j.amepre.2011.10.016

Bamidis, P. D., Vivas, A. B., Styliadis, C., Frantzidis, C., Klados, M., Schlee, W., Siountas, A., & Papageorgiou, S. G. (2014). A review of physical and cognitive interventions in aging. *Neuroscience and Biobehavioral Reviews*, *44*, 206–220. https://doi.org/10.1016/j.neubiorev.2014.03.019

Bamidis, Panagiotis D, Fissler, P., Papageorgiou, S. G., Zilidou, V., Konstantinidis, E. I., Billis, A. S., Romanopoulou, E., Karagianni, M., Beratis, I., Tsapanou, A., Tsilikopoulou, G., Grigoriadou, E., Ladas, A., Kyrillidou, A., Tsolaki, A., Frantzidis, C., Sidiropoulos, E., Siountas, A., Matsi, S., Papatriantafyllou, J., Margioti, E., Nika, A., Schlee, W., Elbert, T., Tsolaki, M., Vivas, A.B., & Kolassa, I. T. (2015). Gains in cognition through combined cognitive and physical training: The role of training dosage and severity of neurocognitive disorder. *Frontiers in Aging Neuroscience*, *7*(July), 1–15. https://doi.org/10.3389/fnagi.2015.00152

Baniqued, P. L., Allen, C. M., Kranz, M. B., Johnson, K., Sipolins, A., Dickens, C., Ward, N., Geyer, A., & Kramer, A. F. (2015). Working memory, reasoning, and task switching training: Transfer effects, limitations, and great expectations? *PLoS ONE*, *10*(11), 1–29. https://doi.org/10.1371/journal.pone.0142169

Barcelos, N., Shah, N., Cohen, K., Hogan, M. J., Mulkerrin, E., Arciero, P. J., Cohen, B.D., Kramer, A.F., & Anderson-Hanley, C. (2015). Aerobic and cognitive exercise (ACE) pilot study for older adults: Executive function improves with cognitive challenge while exergaming. *Journal of the International Neuropsychological Society*, *21*(10), 768–779. https://doi.org/10.1017/S1355617715001083

Bartley, C. A., Hay, M., & Bloch, M. H. (2013). Meta-analysis: Aerobic exercise for the treatment of anxiety disorders. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, *45*, 34–39. https://doi.org/10.1016/j.pnpbp.2013.04.016

Basak, C., Boot, W. R., Voss, M. W., & Kramer, A. F. (2008). Can training in a real-time strategy video game attenuate cognitive decline in older adults? *Psychology and Aging*, *23*(4), 765–777. https://doi.org/10.1037/a0013494

Bates, S. L., & Wolbers, T. (2014). How cognitive aging affects multisensory integration of navigational cues. *Neurobiology of Aging*, *35*(12), 2761–2769. https://doi.org/10.1016/j.neurobiolaging.2014.04.003

Beauchet, O., Annweiler, C., Montero-Odasso, M., Fantino, B., Herrmann, F. R., & Allali, G. (2012). Gait control: A specific subdomain of executive function? *Journal of NeuroEngineering and Rehabilitation*, *9*(1), 1–5. https://doi.org/10.1186/1743-0003-9-12

Belleville, S., & Bherer, L. (2012). Biomarkers of cognitive training effects in aging. *Current Translational Geriatrics and Experimental Gerontology Reports*, *1*(2), 104–110. https://doi.org/10.1007/s13670-012-0014-5

Bender, F., Gorbati, M., Cadavieco, M. C., Denisova, N., Gao, X., Holman, C., Korotkova, T., & Ponomarenko, A. (2015). Theta oscillations regulate the speed of locomotion via a hippocampus to lateral septum pathway. *Nature Communications*, *6*(May) 1-11. https://doi.org/10.1038/ncomms9521

Beyer, K. B., Sage, M.D., Staines, W.R., Middleton, L.E., & McIlroy, W.E. (2017). A single aerobic exercise session accelerates movement execution but not central processing. *Neuroscience*, *346,* 149-159. http://dx.doi.org/10.1016/j.neuroscience.2017.01.020

Bherer, L. (2015). Cognitive plasticity in older adults: Effects of cognitive training and physical exercise. *Annals of the New York Academy of Sciences*, *1337*(1), 1–6. https://doi.org/10.1111/nyas.12682

Billinger, S. a., Boyne, P., Coughenour, E., Dunning, K., & Mattlage, A. (2014). Does Aerobic Exercise and the FITT Principle Fit into Stroke Recovery? *Current Neurology and Neuroscience Reports*, *15*(2) 1-8. https://doi.org/10.1007/s11910-014-0519-8

Binder, J. C., Zöllig, J., Eschen, A., Mérillat, S., Röcke, C., Schoch, S. F., Jancke, L., & Martin, M. (2015). Multi-domain training in healthy old age: Hotel Plastisse as an iPad-based serious game to systematically compare multi-domain and single-domain training. *Frontiers in Aging Neuroscience*, *7*(JUL), 1–22. https://doi.org/10.3389/fnagi.2015.00137

Blacker, K. J., Curby, K. M., Klobusicky, E., & Chein, J. M. (2014). Effects of action video game training on visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(5), 1992–2004. https://doi.org/10.1037/a0037556

Boksem, M. A. S., & Tops, M. (2008). Mental fatigue: Costs and benefits. *Brain Research Reviews*, *59*(1), 125–139. https://doi.org/10.1016/j.brainresrev.2008.07.001

Bolduc, V., Thorin-Trescases, N., & Thorin, E. (2013). Endothelium-dependent control of cerebrovascular functions through age: exercise for healthy cerebrovascular aging. *American Journal of Physiology-Heart and Circulatory Physiology*, *305*(5), H620–H633. https://doi.org/10.1152/ajpheart.00624.2012

Boström, P. A., Graham, E. L., Georgiadi, A., & Ma, X. (2013). Impact of exercise on muscle and nonmuscle organs. *IUBMB Life*, *65*(10), 845–850. https://doi.org/10.1002/iub.1209

Brancucci, A. (2012). Neural correlates of cognitive ability. *Journal of Neuroscience Research*, *90*(7), 1299–1309. https://doi.org/10.1002/jnr.23045

Brunyé, T. T. (2018). Modulating spatial processes and navigation via transcranial electrical stimulation: A mini review. *Frontiers in Human Neuroscience*, *11*(January), 1–8. https://doi.org/10.3389/fnhum.2017.00649

Cassilhas, R. C., Lee, K. S., Fernandes, J., Oliveira, M. G. M., Tufik, S., Meeusen, R., & De Mello, M. T. (2012). Spatial memory is improved by aerobic and resistance exercise through divergent molecular mechanisms. *Neuroscience*, *202*, 309–317. https://doi.org/10.1016/j.neuroscience.2011.11.029

Cassilhas, Ricardo C., Tufik, S., & De Mello, M. T. (2016). Physical exercise, neuroplasticity, spatial learning and memory. *Cellular and Molecular Life Sciences*, *73*(5), 975–983. https://doi.org/10.1007/s00018-015-2102-0

Chang, Y.-K., Chi, L., Etnier, J. L., Wang, C.-C., Chu, C.-H., & Zhou, C. (2014). Effect of acute aerobic exercise on cognitive performance: Role of cardiovascular fitness. *Psychology of Sport and Exercise*, *15*(5), 464–470. https://doi.org/10.1016/j.psychsport.2014.04.007

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research*, *1453*(250), 87–101. https://doi.org/10.1016/j.brainres.2012.02.068

Chapman, S. B., Aslan, S., Spence, J. S., Hart, J. J., Bartz, E. K., Didehbani, N., Keebler, M.W., Gardner, C.M., Strain, J.F., DeFina, L.F., & Lu, H. (2015). Neural mechanisms of brain plasticity with complex cognitive training in healthy seniors. *Cerebral Cortex*, *25*(2), 396–405. https://doi.org/10.1093/cercor/bht234

Colcombe S.J., Erickson K.I., Scalf P.E., Kim J.S., Prakash R., McAuley E., Elavsky S., Marquez D.X., Hu L., K. A. F. (2006). Aerobic exercise training increases brain volume in aging humans. *Journals of Gerontology - Series A Biological Sciences and Medical Sciences*, *61*(11), 1166–1170. https://doi.org/10.1093/gerona/61.11.1166

Colcombe, Stanley J, Erickson, K. I., Raz, N., Webb, A. G., Cohen, N. J., McAuley, E., & Kramer, A. F. (2003). Aerobic fitness reduces brain tissue loss in aging humans. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *58*(2), 176–180. https://doi.org/10.1093/gerona/58.2.M176

Colcombe, S. J., Kramer, A. F., Erickson, K. I., Scalf, P., McAuley, E., Cohen, N. J., Webb, A., Jerome, G.J., Marquez, D.X., & Elavsky, S. (2004). Cardiovascular fitness, cortical plasticity, and aging. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(9), 3316–3321. https://doi.org/10.1073/pnas.0400266101

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), 201–215. https://doi.org/10.1038/nrn755

Cotman, C. W., & Berchtold, N. C. (2002). Exercise: A behavioral intervention to enhance brain health and plasticity. *Trends in Neurosciences*, *25*(6), 295–301.

Cotman, C. W., Berchtold, N. C., & Christie, L. A. (2007). Exercise builds brain health: key roles of growth factor cascades and inflammation. *Trends in Neurosciences*, *30*(9), 464–472. https://doi.org/10.1016/j.tins.2007.06.011

Das, J. P., & Heemsbergen, D. B. (1983). Planning as a factor in the assessment of cognitive processes. *Journal of Psychoeducational Assessment*, *1*(1), 1–15. https://doi.org/10.1177/073428298300100101

Desjardins-Crepeau, L., Berryman, N., Fraser, S. A., Vu, T. T. M., Kergoat, M-J., Li, K. Z. H., Bosquet, L., & Bherer, L. (2016). Effects of combined physical and cognitive training on fitness and neuropsychological outcomes in healthy older adults. *Clinical Interventions in Aging*, *11*, 1287–1299. https://doi.org/10.2147/CIA.S115711

Diamond, A. (2013). Executive functions. *Anual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Eggenberger, P., Schumacher, V., Angst, M., Theill, N., & de Bruin, E. D. (2015). Does multicomponent physical exercise with simultaneous cognitive training boost cognitive performance in older adults? A 6-month randomized controlled trial with a 1-year follow-up. *Clinical Interventions in Aging*, *10*, 1335–1349.

Enriquez-Geppert, S., Huster, R. J., & Herrmann, C. S. (2013). Boosting brain functions: Improving executive functions with behavioral training, neurostimulation, and neurofeedback. *International Journal of Psychophysiology*, *88*(1), 1–16. https://doi.org/10.1016/j.ijpsycho.2013.02.001

Epstein, R. A., Patai, E. Z., Julian, J. B., & Spiers, H. J. (2017). The cognitive map in humans: Spatial navigation and beyond. *Nature Neuroscience*, *20*(11), 1504–1513. https://doi.org/10.1038/nn.4656

Epstein, R. A., & Vass, L. K. (2014). Neural systems for landmark-based wayfinding in humans. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369* (20120533), 1-7. https://doi.org/10.1098/rstb.2012.0533

Erickson, K. I., Gildengers, A. G., & Butters, M. A. (2013). Physical activity and brain plasticity in late adulthood. *Dialogues in Clinical Neuroscience*, *15*, 99–108.

Erickson, K. I., Voss, M. W., Shaurya, R., Basak, C., & Szabo, A. (2011). Exercise training increases size of hippocampus and improves memory. *Proceedings of the National Academy of Sciences*, *108*(7), 3017–3022. https://doi.org/10.1073/pnas.1015950108

Etnier, J. L., & Chang, Y. (2009). The effect of physical activity on executive function: A brief commentary on definitions , measurement issues , and the current state of the literature. *Journal of Sport and Exercise Psychology*, *31*, 469–483.

Fabel, K., Wolf, S. A., Ehninger, D., Baby, H., Leal-Galicia, P., & Kempermann, G. (2009). Additive effects of physical exercise and environmental enrichment on adult hippocampal neurogenesis in mice. *Frontiers in Neuroscience*, *3*(Article 50), 1–7. https://doi.org/10.3389/neuro.22.002.2009

Falbo, S., Condello, G., Capranica, L., Forte, R., & Pesce, C. (2016). Effects of physical-cognitive dual task training on executive function and gait performance in older adults: a randomized controlled trial. *BioMed Research International,* (Article ID 5812092), 1-12.

Fischer, M. H. (2001). Probing spatial working memory with the corsi blocks task. *Brain and Cognition*, *45*, 143–154. https://doi.org/10.1006/brcg.2000.1221

Gallotti, R., Porter, M. A., & Barthelemy, M. (2016). Information measures and cognitive limits in multilayer navigation. *Science Advances*, (February), 1–7.

Grealy, M. A., Johnson, D. A., & Rushton, S. K. (1999). Improving cognitive function after brain injury: The use of exercise and virtual reality. *Archives of Physical Medicine and Rehabilitation*, *80*(6), 661–667. https://doi.org/10.1016/S0003-9993(99)90169-7

Hall, P. A., & Marteau, T. M. (2014). Executive function in the context of chronic disease prevention: Theory, research and practice. *Preventive Medicine*, *68*, 44–50. https://doi.org/10.1016/j.ypmed.2014.07.008

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in Psychology*, *52*, 139–183.

Heekeren, H. R., Marrett, S., & Ungerleider, L. G. (2008). The neural systems that mediate human perceptual decision making. *Nature Reviews Neuroscience*, *9*(6), 467–479. https://doi.org/10.1038/nrn2374

Heinonen, I., Kalliokoski, K. K., Hannukainen, J. C., Duncker, D. J., Nuutila, P., & Knuuti, J. (2014). Organ-specific physiological responses to acute physical exercise and long-term training in humans. *Physiology (Bethesda)*, *29*(6), 421–436. https://doi.org/10.1152/physiol.00067.2013

Hillman, C. H., Pontifex, M. B., Motl, R. W., O'Leary, K. C., Johnson, C. R., Scudder, M. R., Raine, L.B., & Castelli, D. M. (2012). From ERPs to academics. *Developmental Cognitive Neuroscience*, *2S*(SUPPL. 1), S90–S98. https://doi.org/10.1016/j.dcn.2011.07.004

Hötting, K., Holzschneider, K., Stenzel, A., Wolbers, T., & Röder, B. (2013). Effects of a cognitive training on spatial learning and associated functional brain activations. *BMC Neuroscience*, *14*(73), 1–16. https://doi.org/10.1186/1471-2202-14-73

Hötting, K., & Röder, B. (2013). Beneficial effects of physical exercise on neuroplasticity and cognition. *Neuroscience and Biobehavioral Reviews*, *37*(9), 2243–2257. https://doi.org/10.1016/j.neubiorev.2013.04.005

Hsu, C. L., Best, J. R., Chiu, B. K., Nagamatsu, L. S., Voss, M. W., Handy, T. C., Bolandzadeh, N., & Liu-Ambrose, T. (2016). Structural neural correlates of impaired mobility and subsequent decline in executive functions: A 12-month prospective study. *Experimental Gerontology*, *80*, 27–35.

Huang, V., Young, M., & Fiocco, A. J. (2017). The association between video game play and cognitive function: Does gaming platform matter? *Cyberpsychology, Behavior, and Social Networking*, *20*(11), 689–694. https://doi.org/10.1089/cyber.2017.0241

Kaplan, R., Doeller, C. F., Barnes, G. R., Litvak, V., Düzel, E., Bandettini, P. A., & Burgess, N. (2012). Movement-related theta rhythm in humans: Coordinating self-directed hippocampal learning. *PLoS Biology*, *10*(2), 1–13. https://doi.org/10.1371/journal.pbio.1001267

Kelly, M. E., Loughrey, D., Lawlor, B. A., Robertson, I. H., Walsh, C., & Brennan, S. (2014). The impact of cognitive training and mental stimulation on cognitive and everyday functioning of healthy older adults: A systematic review and meta-analysis. *Ageing Research Reviews*, *15*(1), 28–43. https://doi.org/10.1016/j.arr.2014.02.004

Kempermann, G., Fabel, K., Ehninger, D., Babu, H., Leal-Galicia, P., Garthe, A., & Wolf, S. A. (2010). Why and how physical activity promotes experience-induced brain plasticity. *Frontiers in Neuroscience*, *4*(Article 189), 1–9. https://doi.org/10.3389/fnins.2010.00189

Korotkova, T., Ponomarenko, A., Monaghan, C. K., Poulter, S. L., Cacucci, F., Wills, T., Hasselmo, M.E., & Lever, C. (2018). Reconciling the different faces of hippocampal theta: The role of theta oscillations in cognitive, emotional and innate behaviors. *Neuroscience and Biobehavioral Reviews*, *85*(September 2017), 65–80. https://doi.org/10.1016/j.neubiorev.2017.09.004

Kramer, A. F., & Erickson, K. I. (2007). Capitalizing on cortical plasticity: Influence of physical activity on cognition and brain function. *Trends in Cognitive Sciences*, *11*(8), 342–348. https://doi.org/10.1016/j.tics.2007.06.009

Kravitz, D. J., Saleem, K. S., Baker, C. I., & Mishkin, M. (2011). A new neural framework for visuospatial processing. *Nature Reviews Neuroscience*, *12*, 217–230.

Kühn, S., Gleich, T., Lorenz, R. C., Lindenberger, U., & Gallinat, J. (2014). Playing super mario induces structural brain plasticity: Gray matter changes resulting from training with a commercial video game. *Molecular Psychiatry*, *19*(2), 265–271. https://doi.org/10.1038/mp.2013.120

Lauenroth, A., Ioannidis, A. E., & Teichmann, B. (2016). Influence of combined physical and cognitive training on cognition: A systematic review. *BMC Geriatrics*, *16*(141), 1–14. https://doi.org/10.1186/s12877-016-0315-1

Levac, D., Glegg, S., Colquhoun, H., Miller, P., & Noubary, F. (2017). Virtual reality and active videogame-based practice, learning aeeds, and preferences: A cross-Canada survey of Physical Therapists and Occupational Therapists. *Games for Health Journal*, *6*(4), 217–228. https://doi.org/10.1089/g4h.2016.0089

Liu-Ambrose, T., Katarynych, L. A., Ashe, M. C., Nagamatsu, L. S., & Chun, L. H. (2009). Dual-task gait performance among community-dwelling senior women: The role of balance confidence and executive functions. *Journals of Gerontology - Series A Biological Sciences and Medical Sciences*, *64*(9), 975–982. https://doi.org/10.1093/gerona/glp063

Logue, S. F., & Gould, T. J. (2014). The neural and genetic basis of executive function: Attention, cognitive flexibility, and response inhibition. *Pharmacology Biochemistry and Behavior*, *123*, 45–54. https://doi.org/10.1016/j.pbb.2013.08.007

Lövdén, M., Herlitz, A., Schellenbach, M., Grossman-Hutter, B., Krüger, A., & Lindenberger, U. (2007). Quantitative and qualitative sex differences in spatial navigation: Cognition and neurosciences. *Scandinavian Journal of Psychology*, *48*(5), 353–358. https://doi.org/10.1111/j.1467-9450.2007.00582.x

Lövdén, M., Schaefer, S., Noack, H., Bodammer, N. C., Kühn, S., Heinze, H. J., Düzel, E., Backman, L., & Lindenberger, U. (2012). Spatial navigation training protects the hippocampus against age-related changes during early and late adulthood. *Neurobiology of Aging*, *33*(3), 620.e9-620.e22. https://doi.org/10.1016/j.neurobiolaging.2011.02.013

Ludyga, S., Gerber, M., Brand, S., Holsboer-Trachsler, E., & Pühse, U. (2016). Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. *Psychophysiology*, *53*(11), 1611–1626. https://doi.org/10.1111/psyp.12736

Magistretti, P. J., & Allaman, I. (2018). Lactate in the brain: From metabolic end-product to signalling molecule. *Nature Reviews Neuroscience*, *19*(4), 235–249. https://doi.org/10.1038/nrn.2018.19

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., & Firth, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences*, *97*(8), 4398–4403. https://doi.org/10.1093/jac/46.1.73

Marusic, U., Verghese, J., & Mahoney, J. R. (2018). Cognitive-based interventions to improve mobility: A systematic review and meta-analysis. *Journal of the American Medical Directors Association*, *19*(6), 484–491. https://doi.org/10.1016/j.jamda.2018.02.002

Micklewright, D., St Clair Gibson, A., Gladwell, V., & Al Salman, A. (2017). Development and validity of the Rating-of-Fatigue scale. *Sports Medicine*, *47*(11), 2375–2393. https://doi.org/10.1007/s40279-017-0711-5

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*, 167–202.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Miyasike-DaSilva, V., Allard, F., & McIlroy, W.E. (2011). Where do we look when we walk on stairs? Gaze behaviour on stairs, transitions, and handrails. *Experimental Brain Research, 209*(1), 73-83.

Moffat, S. D. (2009). Aging and spatial navigation: What do we know and where do we go? *Neuropsychology Review*, *19*(4), 478–489. https://doi.org/10.1007/s11065-009-9120-3

Momi, D., Smeralda, C., Sprugnoli, G., Ferrone, S., Rossi, S., Rossi, A., Lorenzo, G.D., & Santarnecchi, E. (2018). Acute and long-lasting cortical thickness changes following intensive first-person action videogame practice. *Behavioural Brain Research*, *353*, 62–73. https://doi.org/10.1016/j.bbr.2018.06.013

Mora, F. (2013). Successful brain aging: Plasticity, environmental enrichment, and lifestyle. *Dialogues in Clinical Neuroscience*, *15*(1), 45–52.

Moser, E. I., Roudi, Y., Witter, M. P., Kentros, C., Bonhoeffer, T., & Moser, M. B. (2014). Grid cells and cortical representation. *Nature Reviews Neuroscience*, *15*(7), 466–481. https://doi.org/10.1038/nrn3766

Moser, M.-B., Rowland, D. C., & Moser, E. I. (2015). Place cells, grid cells, and memory. *Cold Spring Harbor Perspectives in Biology*, *7*, 1–16.

Münzer, S., Zimmer, H. D., & Baus, J. (2012). Navigation assistance: A trade-off between wayfinding support and configural learning support. *Journal of Experimental Psychology: Applied*, *18*(1), 18–37. https://doi.org/10.1037/a0026553

Nadkarni, N. K., Zabjek, K., Lee, B., McIlroy, W. E., & Black, S. E. (2010). Effect of working memory and spatial attention tasks on gait in healthy young and older adults. *Motor Control*, *14*(2), 195–210. https://doi.org/10.1038/jid.2014.371

Nagamatsu, L. S., Voss, M. W., Neider, M. B., Gaspar, J. G., Handy, T. C., Kramer, A. F., & Liu-Ambrose, T. Y. (2011). Increased cognitive load leads to impaired mobility decisions in seniors at risk for falls. *Psychology and Aging*, *26*(2), 253–259. https://doi.org/10.1038/jid.2014.371

O'Leary, K. C., Pontifex, M. B., Scudder, M. R., Brown, M. L., & Hillman, C. H. (2011). The effects of single bouts of aerobic exercise, exergaming, and videogame play on cognitive control. *Clinical Neurophysiology*, *122*(8), 1518–1525. https://doi.org/10.1016/j.clinph.2011.01.049

Oei, A. C., & Patterson, M. D. (2013). Enhancing cognition with video games: A multiple game training study. *PLoS ONE*, *8*(3), 1–16. https://doi.org/10.1371/journal.pone.0058546

Ogawa, E. F., You, T., & Leveille, S. G. (2016b). Potential benefits of exergaming for cognition and dual-task function in older adults: A systematic review. *Journal of Aging and Physical Activity*, *24*(2), 332–336. https://doi.org/10.1123/japa.2014-0267

Pedroli, E., Greci, L., Colombo, D., Serino, S., Cipresso, P., Arlati, S., Mondellini, M., Boilini, L., Giussani, V., Goulene, K., Agostoni, M., Sacco, M., Stramba-Badiale, M., Riva, G., & Gaggioli, A. (2018). Characteristics, usability, and users experience of a system combining cognitive and physical therapy in a virtual environment: Positive bike. *Sensors (Switzerland)*, *18*(7) 1–16. https://doi.org/10.3390/s18072343

Phillips, C. (2017). Lifestyle modulators of neuroplasticity: How physical activity, mental engagement, and diet promote cognitive health during aging. *Neural Plasticity*, (Article ID 3589271), 1–22. https://doi.org/10.1155/2017/3589271

Plummer, P., & Eskes, G. (2015). Measuring treatment effects on dual-task performance: A framework for research and clinical practice. *Frontiers in Human Neuroscience*, *9*(Article 225), 1–7. https://doi.org/10.3389/fnhum.2015.00225

Raz, N., & Rodrigue, K. M. (2006). Differential aging of the brain: Patterns, cognitive correlates and modifiers. *Neuroscience and Biobehavioral Reviews*, *30*(6), 730–748. https://doi.org/10.1016/j.neubiorev.2006.07.001

Reijnders, J., van Heugten, C., & van Boxtel, M. (2013). Cognitive interventions in healthy older adults and people with mild cognitive impairment: A systematic review. *Ageing Research Reviews*, *12*(1), 263–275. https://doi.org/10.1016/j.arr.2012.07.003

Rivera-Brown, A. M., & Frontera, W. R. (2012). Principles of exercise physiology: Responses to acute exercise and long-term adaptations to training. *Physical Medicine and Rehabilitation*, *4*(11), 797–804. https://doi.org/10.1016/j.pmrj.2012.10.007

Schaefer, S., & Schumacher, V. (2011). The interplay between cognitive and motor functioning in healthy older adults: Findings from dual-task studies and suggestions for intervention. *Gerontology*, *57*(3), 239–246. https://doi.org/10.1159/000322197

Schuch, F. B., Vancampfort, D., Richards, J., Rosenbaum, S., Ward, P. B., & Stubbs, B. (2016). Exercise as a treatment for depression: A meta-analysis adjusting for publication bias. *Journal of Psychiatric Research*, *77*, 42–51. https://doi.org/10.1016/j.jpsychires.2016.02.023

Shaffer, J. (2016). Neuroplasticity and clinical practice: Building brain power for health. *Frontiers in Psychology*, *7*(Article 1118), 1–12. https://doi.org/10.3389/fpsyg.2016.01118

Shatil, E. (2013). Does combined cognitive training and physical activity training enhance cognitive abilities more than either alone? A four-condition randomized controlled trial among healthy older adults. *Frontiers in Aging Neuroscience*, *5*(Article 8), 1–12. https://doi.org/10.3389/fnagi.2013.00008

Shatil, E., Mikulecka, J., Bellotti, F., & Bure, V. (2014). Novel television-based cognitive training improves working memory and executive function. *PLoS ONE*, *9*(7), e101472. https://doi.org/10.1371/journal.pone.0101472

Shin, J. D., & Jadhav, S. P. (2016). Multiple modes of hippocampal–prefrontal interactions in memory-guided behavior. *Current Opinion in Neurobiology*, *40*, 161–169. https://doi.org/10.1016/j.conb.2016.07.015

Sibley, K. M., Tang, A., Brooks, D., Brown, D. A., & McIlroy, W. E. (2008). Feasibility of adapted aerobic cycle ergometry tasks to encourage paretic limb use after stroke: A case series. *Journal of Neurologic Physical Therapy*, *32*(2), 80–87. https://doi.org/10.1097/NPT.0b013e318176b466

Spiers, H. J., & Gilbert, S. J. (2015). Solving the detour problem in navigation: A model of prefrontal and hippocampal interactions. *Frontiers in Human Neuroscience*, *9*(MAR), 1–15. https://doi.org/10.3389/fnhum.2015.00125

Spiers, H. J., & Maguire, E. A. (2008). The dynamic nature of cognition during wayfinding. *Journal of Environmental Psychology*, *28*(3), 232–249. https://doi.org/10.1016/j.jenvp.2008.02.006

Stillman, C. M., Cohen, J., Lehman, M. E., & Erickson, K. I. (2016). Mediators of physical activity on neurocognitive function: A review at multiple levels of analysis. *Frontiers in Human Neuroscience*, *10*(Article 626), 1–17. https://doi.org/10.3389/fnhum.2016.00626

Taillade, M., Sauzéon, H., Dejos, M., Pala, Prashant, A., Larrue, F., Wallet, G., Gross, C., & N'Kaoua, B. (2013). Executive and memory correlates of age-related differences in wayfinding performances using a virtual reality application. *Aging, Neuropsychology, and Cognition*, *20*(3), 298–319.

Tait, J. L., Duckham, R. L., Milte, C. M., Main, L. C., & Daly, R. M. (2017). Influence of sequential vs. simultaneous dual-task exercise training on cognitive function in older adults. *Frontiers in Aging Neuroscience*, *9*(Article 368), 1–10. https://doi.org/10.3389/fnagi.2017.00368

Tang, A., Sibley, K.M., Thomas, S.G., Bayley, M.T., Richardson, D., McIlroy, W.E., & Brooks, D. (2009). Effects of an aerobic exercise program on aerobic capacity, spatiotemporal gait parameters, and functional capacity in subacute stroke. *Neurorehabilitation & Neural Repair*, *23*(4), 398-406.

Tanji, J., & Hoshi, E. (2001). Behavioral planning in the prefrontal cortex. *Current Opinion in Neurobiology*, *11*, 164–170.

Valtchanov, D., Barton, K. R., & Ellard, C. (2010). Restorative effects of virtual nature settings. *Cyberpsychology, Behavior, and Social Networking*, *13*(5), 503–512. https://doi.org/10.1089/cyber.2009.0308

Valtchanov, D., & Ellard, C. (2010). Physiological and affective responses to immersion in virtual reality: Effects of nature and urban settings. *Journal of CyberTherapy & Rehabilitation*, *3*(4), 359–373.

Van Cutsem, J., Marcora, S., De Pauw, K., Bailey, S., Meeusen, R., & Roelands, B. (2017). The effects of mental fatigue on physical performance: A systematic review. *Sports Medicine*, *47*(8), 1569–1588. https://doi.org/10.1007/s40279-016-0672-0

Vercruyssen, F., & Brisswalter, J. (2010). Which factors determine the freely chosen cadence during submaximal cycling? *Journal of Science and Medicine in Sport*, *13*(2), 225–231. https://doi.org/10.1016/j.jsams.2008.12.631

Voss, M. W., Vivar, C., Kramer, A. F., & van Praag, H. (2013). Bridging animal and human models of exercise-induced brain plasticity. *Trends in Cognitive Sciences*, *17*(10), 525–544. https://doi.org/10.1016/j.tics.2013.08.001

Warlop, T. B., Bollens, B., Crevecoeur, F., Detrembleur, C., & Lejeune, T. M. (2013). Dynamics of revolution time variability in cycling pattern: Voluntary intent can alter the long-range autocorrelations. *Annals of Biomedical Engineering*, *41*(8), 1604–1612. https://doi.org/10.1007/s10439-013-0834-2

Weinstein, A. M., Voss, M. W., Prakash, R. S., Chaddock, L., Szabo, A., White, S. M., Wojcicki, T.R., Mailey, E., McAuley, D., Kramer, A.F., & Erickson, K. I. (2012). The association between aerobic fitness and executive function is mediated by prefrontal cortex volume. *Brain, Behavior, and Immunity*, *26*(5), 811–819. https://doi.org/10.1016/j.bbi.2011.11.008

West, G. L., Drisdelle, B. L., Konishi, K., Jackson, J., Jolicoeur, P., & Bohbot, V. D. (2015). Habitual action video game playing is associated with caudate nucleusdependent navigational strategies. *Proceedings of the Royal Society B: Biological Sciences*, *282*(20142952), 1–9. https://doi.org/10.1098/rspb.2014.2952

Whitty, A. G., Murphy, A. J., Coutts, A. J., & Watsford, M. L. (2009). Factors associated with the selection of the freely chosen cadence in non-cyclists. *European Journal of Applied Physiology*, *106*(5), 705–712. https://doi.org/10.1007/s00421-009-1071-0

Wiener, J. M., Büchner, S. J., & Hölscher, C. (2009). Taxonomy of human wayfinding tasks: A knowledge-based approach. *Spatial Cognition and Computation*, *9*(2), 152–165. https://doi.org/10.1080/13875860902906496

Wilson, M. G., Ellison, G. M., & Cable, N. T. (2015). Basic science behind the cardiovascular benefits of exercise. *Heart*, *101*(10), 758–765. https://doi.org/10.1136/heartjnl-2014-306596

Wolbers, T., & Hegarty, M. (2010). What determines our navigational abilities? *Trends in Cognitive Sciences*, *14*(3), 138–146. https://doi.org/10.1016/j.tics.2010.01.001

Wolbers, T., Hegarty, M., Buchel, C., & Loomis, J. M. (2008). Spatial updating: How the brain keeps track of changing object locations during observer motion. *Nature Neuroscience*, *11*(10), 1223–1230.

Wolbers, T., & Wiener, J. M. (2014). Challenges for identifying the neural mechanisms that support spatial navigation: The impact of spatial scale. *Frontiers in Human Neuroscience*, *8*(Article 571), 1–12. https://doi.org/10.3389/fnhum.2014.00571

Wong, C. N., Chaddock-Heyman, L., Voss, M. W., Burzynska, A. Z., Basak, C., Erickson, K. I., Prakash, R.S., Szabo-Reed, A.N., Phillips, S.M., Wojcicki, T., Mailey, E.L., McAuley, E., & Kramer, A. F. (2015). Brain activation during dual-task processing is associated with cardiorespiratory fitness and performance in older adults. *Frontiers in Aging Neuroscience*, *7*(Article 154), 1–10. https://doi.org/10.3389/fnagi.2015.00154

Yildiz, A., & Beste, C. (2015). Parallel and serial processing in dual-tasking differentially involves mechanisms in the striatum and the lateral prefrontal cortex. *Brain Structure and Function*, *220*(6), 3131–3142. https://doi.org/10.1007/s00429-014-0847-0

Zimmer, H. D. (2008). Visual and spatial working memory: From boxes to networks. *Neuroscience and Biobehavioral Reviews*, *32*(8), 1373–1395. https://doi.org/10.1016/j.neubiorev.2008.05.016

APPENDIX A: Borg RPE Scale (10 Point Scale)

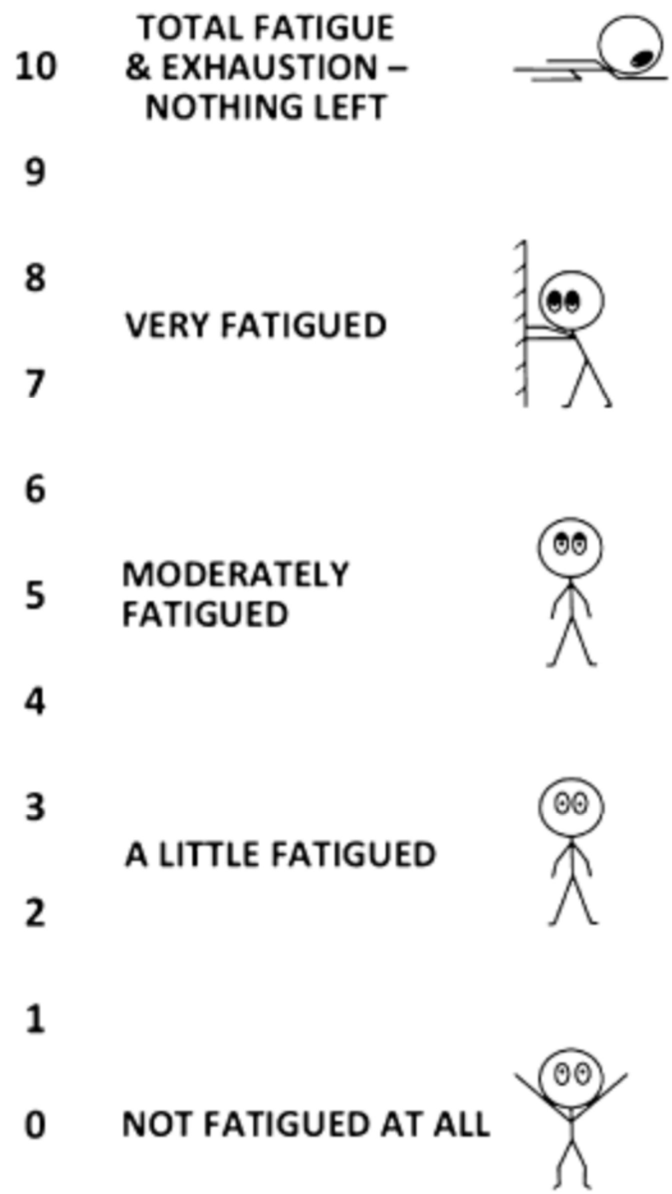
RATE YOUR PERCIEVED EXERTION

0	Nothing at all
0.5	Very, very weak
1	Very weak
2	Weak
3	Moderate
4	Somewhat strong
5	Strong
6	
7	Very strong
8	
9	
10	Very, very strong

Borg, G.V. (1982, pg. 380)

APPENDIX B: Rating of Fatigue Scale

PLEASE RATE YOUR OVERALL LEVEL OF FATIGUE



Micklewright et al. (2017, pg. 2380)

APPENDIX C: NASA Task Load Index

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Hart & Staveland (1988, URL: https://humansystems.arc.nasa.gov/groups/TLX/index.php)

APPENDIX D: Google Earth Task Instructions

This series of tasks will take place in the internet platform of Google Earth and its associated controls. You will be asked to perform spatial navigation tasks within the rendered street view version of Google Earth. This will be performed using a keyboard and a television screen while seated at a desk. The controls are the arrow keys: UP will move you forward, LEFT turns left, RIGHT turns right, and DOWN will enable you to move straight backward, as though you were walking backwards.

You will move at a constant speed through Google Earth. While the program lets you, I ask that you please do not go through or underneath the buildings. Please travel over roads and ground, just as you would when walking.

For this task, you will be asked to find a series of pins that are placed along an unknown route. I will always tell you how many pins you are looking for along the route. You are at PIN 1, and you are currently facing in the direction necessary to find PIN 2. What I would like you to do, is to move from PIN 1 to PIN 2, turn around and go back to PIN1. From there, you will move from 1 to 2 to 3, then turn around at 3 and go all the way back to 1, etc. You will notice that you can see the pin number show up as you approach the pin – this is what it is supposed to happen. Go right up to the pin and then turn around (as necessary) or continue on to the next pin.

This series will continue until you a) reach the end, b) reach a navigation time of 30 minutes (*Study 2*) / 20 minutes (*Studies 3 & 4*), or c) become lost and unable to find your place in the environment.

When performing the dual-task of biking and navigation, the forward pedalling motion of the bike is what is going to propel you forward in Google Earth. Holding the Nintendo Wii joystick in your hand, you will use the joystick to make turns. You will notice that because you are pedalling forward, you cannot turn 'on a dime' unless you cease pedalling to make the turn, and then continue on. Otherwise, the turns will be much wider because you are turning while moving forward. How you choose to successfully complete the task is up to you. (*For Studies 3 & 4*).

There is a program that is going to collect your key strokes of the arrow keys so that I know when you made turns or when you were travelling straight. Google Earth also lets me record a video of your navigation performance that I can get coordinates from to determine how far you travelled. This program records what is occurring on the computer screen, and does not record any video or audio of you in the room.

APPENDIX E: Executive Function Task Instructions

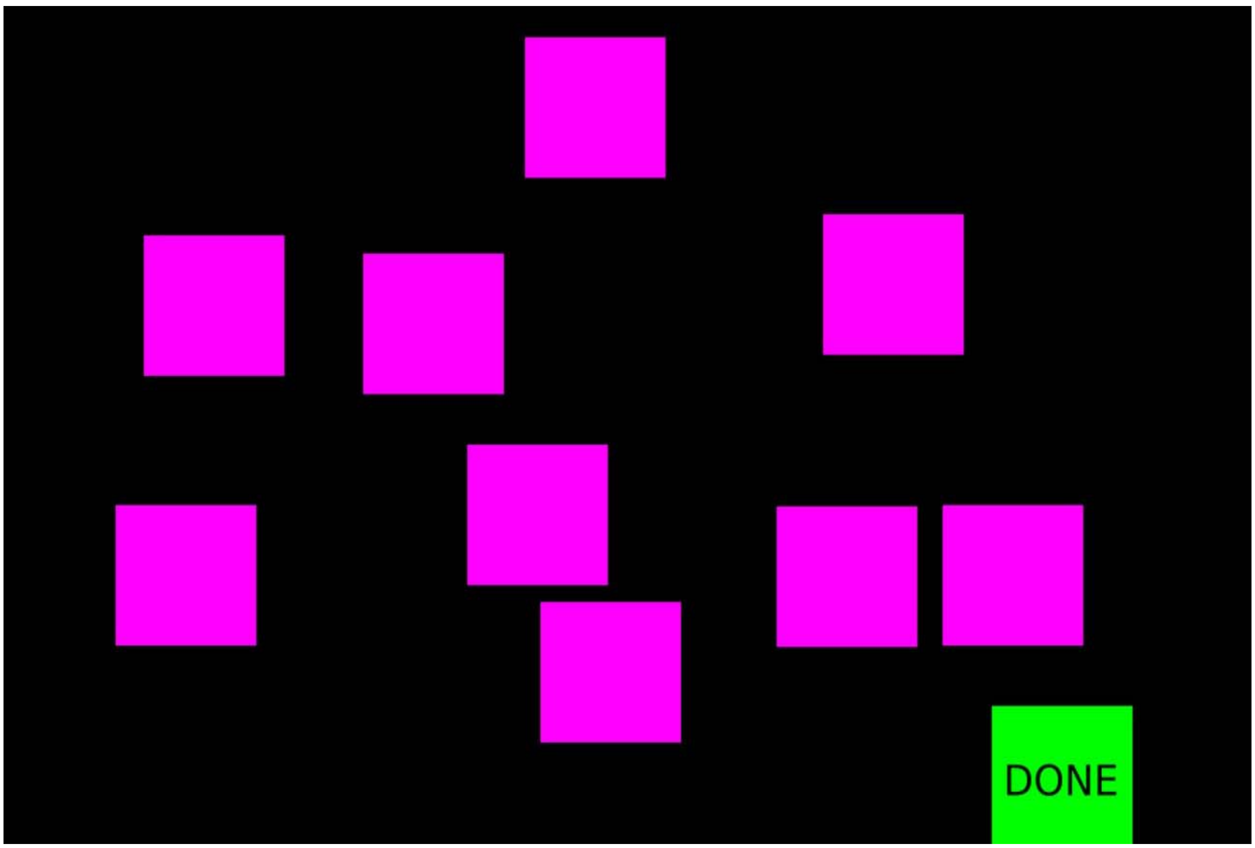
To measure executive function ability, you will be asked to perform numerous computerized executive tasks. For these tasks, you will be seated at a computer and the tasks will be displayed on the computer monitor. The stimuli for the tasks are displayed on the monitor. You will be asked to respond to the stimuli by using the keyboard or the computer mouse, depending on the task.

Stroop Task:

For this task, one of the words YELLOW, RED, GREEN or BLUE will appear on the computer screen. The word could be presented in the same colour as the word (e.g. word RED in red 'ink') or, the word could be presented in a different colour than the word (e.g. word RED in blue 'ink'). In all conditions, you are asked to respond to the colour of the 'ink' and not the colour the word is depicting. Please keep your hands / fingers resting in the "home" position on the keyboard. To indicate your response, you will press the Y key for YELLOW, the R key for RED, the G key for GREEN or the B key for BLUE. Remember, you are to respond to the colour of the "ink", not the word itself. The trial times out after 2 seconds. One block of this task takes approximately 2 minutes to complete, and there are 3 blocks.

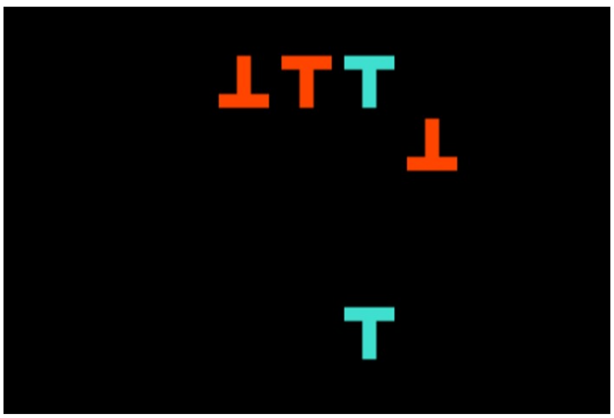
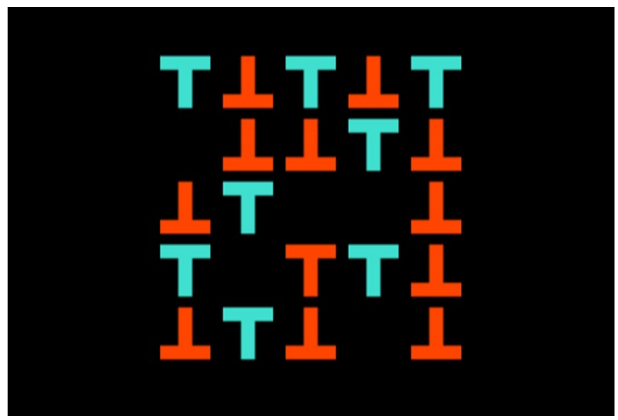
Corsi Block Task:

For this task, a series of 9 boxes appear in random positions across the computer screen. Upon the start of the trial, boxes are quickly illuminated in a randomly sequential order, starting with 2 boxes. You will then use the mouse to click on the boxes, in the order in which they were illuminated, and then click the box that says “Done”. After each successful trial, and additional box is illuminated until you can no longer remember the order of illumination, or you successfully order all 9 boxes. The trial times out after 10 seconds. One block of this task takes approximately 2 minutes to complete and there are 3 blocks



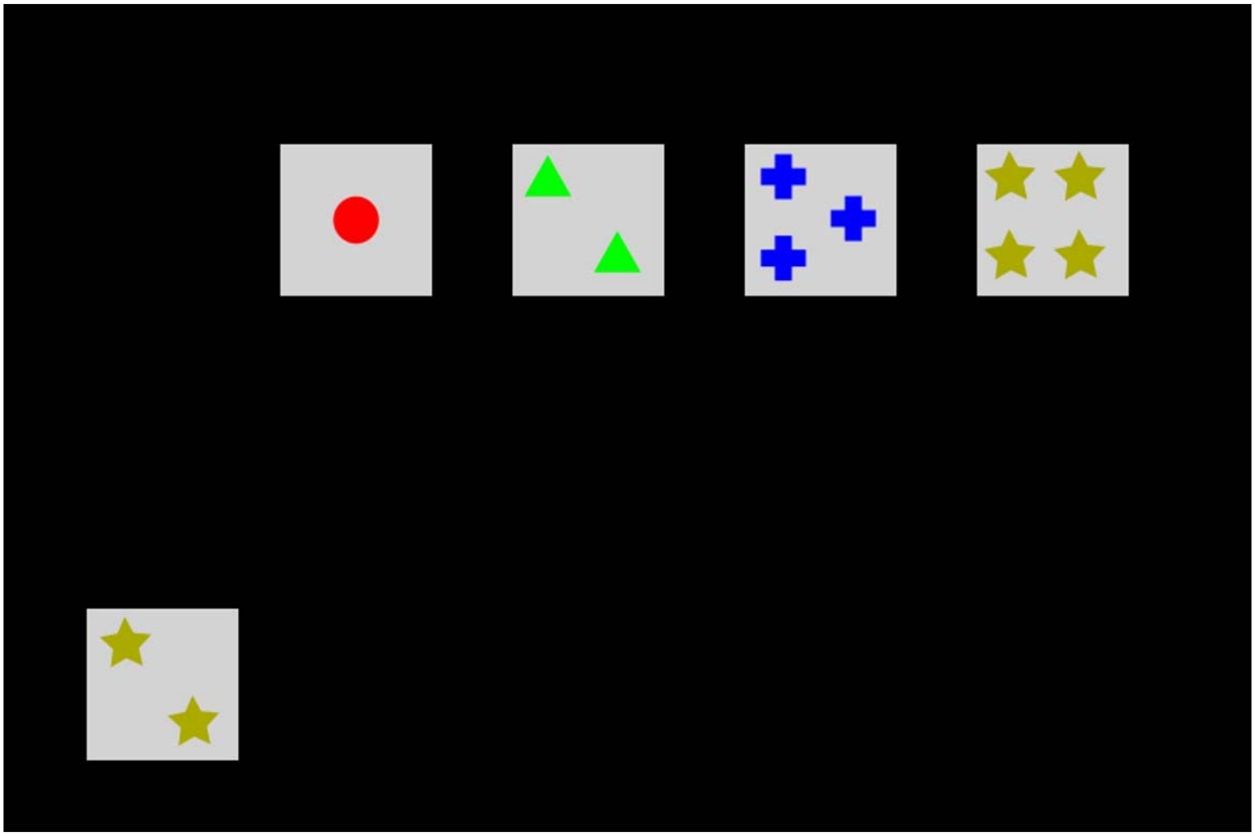
Visual Search Task:

For this task, a series of capital letter "T"s appear in random positions on the computer screen. Some of the "T"s are blue and some are orange, and some "T"s are right-side up while others are upside-down. There will be either a total of 5, 10, 15 or 20 stimuli on the screen. The target stimulus is an upright orange "T". You are asked to respond as quickly as possible when you see the target stimulus by pressing the Space Bar. However, you are also asked to refrain from responding when you do not see the target stimulus. The trial times out after 4 seconds. One block of this task takes approximately 4 minutes and there are 3 blocks.

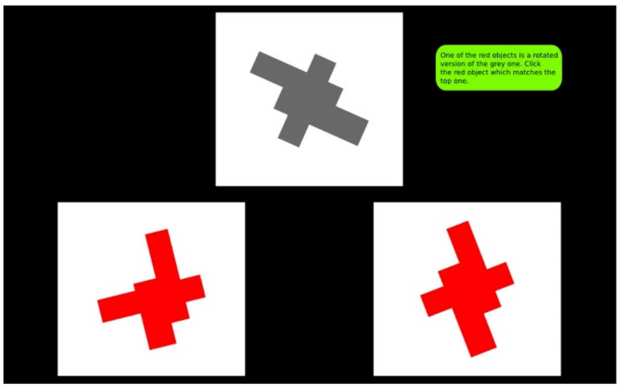
Wisconsin Card Sorting Task:

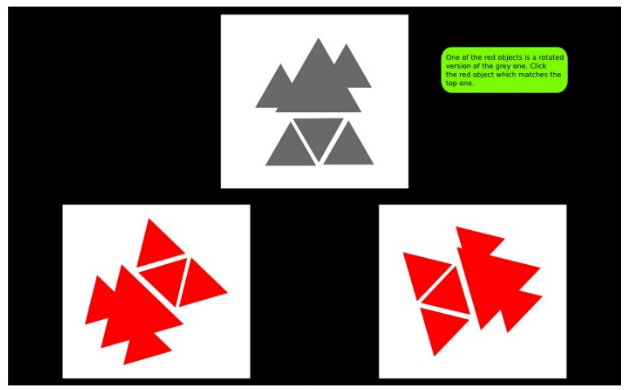
For this task, four target cards are presented across the top of the screen: one red circle, two green triangles, three blue crosses and four yellow stars. A stimulus card is presented on the lower left of the screen, and the stimulus card could have any combination of number of items (1-4), shapes (circle, triangle, crosses or stars), or colours of the shapes. You are asked to match the stimulus card to the appropriate target card – and the match will be based on colour only, shape only, or number of items only. You will receive feedback on the screen as to whether or not you have successfully matched the stimulus card to the target card. However, the rules for what constitutes a 'match' change throughout the game, and you are then required to figure out the new 'match' rule. The trial times out after 5 seconds. One block of this task takes approximately 4 minutes and there are 3 blocks.

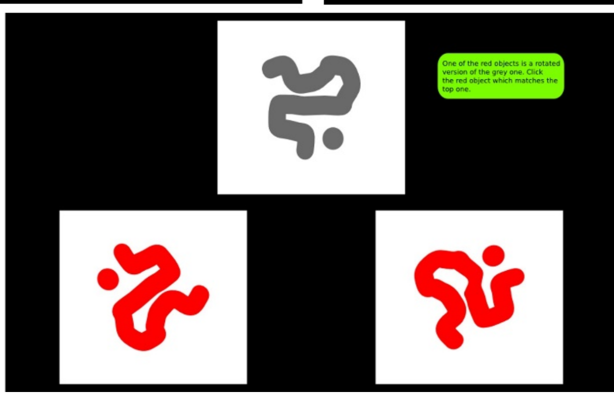


Mental Rotation Task:

For this task, you will see an initial 2D image of a random shape. Beneath it there are two target images, both of which appear as rotated images of the original image. You are asked to use the mouse to click on and identify which rotated image matches the original image. There is a practice block of 5 trials, and then the study block of 10 trials. The trial times out after 10 seconds. One block of trials for this task takes approximately 2 minutes and there is only 1 block for this task.







APPENDIX F: Demographics Survey

Study 2: Navigation Study

Demographic Information

These questions are basic demographic information about you. This information cannot be tied back to your identity, as study participants are assigned an alpha-numeric code that only the Student Investigator has access to. Please answer as accurately as possible.

* 1. Study ID (please ask Student Investigator for this information):

[ ]

* 2. Please enter today's date

Date / Time

DD/MM/YYYY

* 3. Please enter your age in years:

[ ]

* 4. Please identify your gender

- [ ] Female
- [ ] Male
- [ ] Other, and I choose not to disclose
- [ ] Other, and I choose to identify

If you choose to disclose your gender to the researcher, please indicate it in the space below

[ ]

* 5. Please identify your sex

- [ ] Female
- [ ] Male
- [ ] Other, and I choose not to disclose
- [ ] Other, and I choose to identify

If you choose to disclose your sex to the researcher, please indicate it in the space below

* 6. What is your dominant hand?

- [ ] Right
- [ ] Left

* 7. Do you wear prescription glasses or contacts?

- [ ] No
- [ ] Yes

If "YES", please explain what you need vision correction for:

* 8. Are you colour blind?

- [ ] No
- [ ] Yes

If "YES", please explain:

* 9. Do you have any other visual impairments?

- [ ] No
- [ ] Yes

If "YES", please explain:

* 10. Do you experience Motion Sickness?

- [ ] No
- [ ] Yes

* 11. If you answered "YES" to question 10, how would you classify your motion sickness based on the options below, otherwise choose N/A

- [ ] Mild
- [ ] Moderate
- [ ] Severe
- [ ] N/A

* 12. Have you exercised within the past 24 hours?

- [ ] No
- [ ] Yes

If "YES", please explain:

* 13. Have you consumed caffeine today?

- [ ] No
- [ ] Yes

If "YES", please explain:

* 14. Please use this space to elaborate on what activities you have done so far today (e.g. phone use, watch tv, class, midterms etc.):

Study 2: Navigation Study

Educational Background

This section is to gain insight into your current educational background. Please answer as accurately as possible.

* 15. What is your current level of study?:

- [ ] Undergraduate
- [ ] Graduate
- [ ] Other

If "OTHER" please explain:

* 16. What program of study are you currently in?

* 17. Which year of your degree are you in?

Study 2: Navigation Study

Exercise & Activity Background

This section is to gain further insight into your current exercise training habits. Please answer as accurately as possible.

* 18. Approximately how many hours did you exercise in the past 7 days?

* 19. What type(s) of exercise do you participate in? Check all that apply:

- [ ] Cardiovascular (e.g.: cycling, running, swimming)
- [ ] Strength Training (e.g. weight lifting)
- [ ] Balance & Core (e.g. yoga, Pilates)
- [ ] Team Training (e.g. intramural sports, varsity sports)
- [ ] Group led Fitness Classes (e.g. step, Zumba)
- [ ] I do not participate in exercise

* 20. Please use this space to elaborate of your exercise training habits:

* 21. How do you generally participate in exercise? Check the option that applies to how you most often participate in exercise

- [ ] I generally exercise alone
- [ ] I generally exercise with a friend / partner
- [ ] I generally exercise as part of a team
- [ ] I generally exercise as an individual as part of a fitness class or group
- [ ] I do not participate in exercise

Study 2: Navigation Study

Navigation Background

This section is to gain further insight into your current driving and navigation experience. Please answer as accurately as possible.

* 22. Which of the following best describes the environment in which you grew up?

- [ ] Urban - living in a city or town
- [ ] Suburban - living outside of a city or town
- [ ] Rural - living in the country, well outside of a city or town

* 23. Do you own, or have regular access to a vehicle?

- [ ] Yes
- [ ] No

* 24. Did you drive to school / the facility today?

- [ ] Yes
- [ ] No

* 25. Were you a passenger in a vehicle (car/bus) to get to school / the facility today?

- [ ] Yes
- [ ] No

* 26. Have you ever worked a delivery job / Uber job before?

- [ ] Yes
- [ ] No

If "YES" please explain:

* 27. How many days per week do you drive?

* 28. How many hours do you spend driving per week?

* 29. How many days per week are you a passenger in a vehicle? (Not including public transit):

* 30. How many hours per week are you a passenger in a vehicle? (Not including public transit):

* 31. How many days per week do you take public transit?

* 32. How many hours per week are you a passenger on public transit?

Study 2: Navigation Study

Video Game Background

This section is to gain further insight into your current video game playing habits. Please answer as accurately as possible.

* 33. Do you currently play video games?

- [ ] Yes
- [ ] No

* 34. Did you used to play video games but have ceased playing them?

- [ ] Yes
- [ ] No

* 35. What type of system do you generally play video games on? If you do not play video games, please type "N/A"

* 36. How many years have you been playing video games? If you do not play video games, please type "0"

* 37. On average, how many hours per day play video games? If you do not play video games, please type "0"

* 38. Which type of video game do you play the most?

- [ ] Action video games (e.g. shooter games, quests)
- [ ] Strategy video games (e.g. puzzles, chess)
- [ ] None - I don't play video games

* 39. Which type of video game do you play the most?

- [ ] Immersive video games (e.g. first person shooter)
- [ ] Non-Immersive video games (e.g. original Mario Brothers or Donkey Kong)
- [ ] None - I don't play video games

* 40. Have you partaken in video game play so far today?

- [ ] Yes
- [ ] No

41. Please name the top 3 video games that you play the most; If you do not play video games please type "N/A":

1: __________

2: __________

3: __________

Study 2: Navigation Study

Perception Scales

The following questions ask you to estimate how often you participate in an activity or your own abilities on certain tasks. There is no right or wrong answer, just please try to be as accurate as possible in your self reflection.

* 42. How would you rate your overall fitness?

Very Unfit — Very Fit

* 43. How would you rate your own navigation ability?

Very Poor — Excellent

* 44. How often do your drive a motorized vehicle?

Never — Daily

* 45. How often do your drive a non-motorized vehicle (e.g. bicycle)?

Never — Daily

* 46. How often are you a passenger in a motorized vehicle?

Never Daily

* 47. How proficient are you at using maps?

Not At All Highly Proficient

* 48. How dependent are you on using a GPS?

Completely Not At All

* 49. How often do you play video games on a computer / console (NOT tablet/phone)?:

Never Daily

* 50. How often do you play video games on your phone / tablet?:

Never Daily

* 51. How often do you play immersive video games? (e.g. Call of Duty):

Never Daily

* 52. How often do you play non-immersive video games? (e.g. Solitaire):

Never Daily

* 53. How often do you play action style video games?:

Never Daily

* 54. How often do you play non-action strategy video games?:

Never Daily

APPENDIX G: Navigation Scoring System

Pin Order	Score
1	0
2	1
1	2
2	3
3	4
2	5
1	6
2	7
3	8
4	9
3	10
2	11
1	12
2	13
3	14
4	15
5	16
4	17
3	18
2	19
1	20
2	21
3	22
4	23
5	24
6	25
5	26
4	27
3	28
2	29
1	30
2	31
3	32
4	33
5	34
6	35
7	36
6	37
5	38
4	39
3	40
2	41
1	42