USING ORIENTEERING TO EXAMINE THE INTERACTIONS OF EXERCISE AND COGNITIVE TRAINING ON HUMAN COGNITION AND BRAIN-DERIVED NEUROTROPHIC FACTOR

USING ORIENTEERING TO EXAMINE THE INTERACTIONS OF EXERCISE AND COGNITIVE TRAINING ON HUMAN COGNITION AND BRAIN-DERIVED NEUROTROPHIC FACTOR

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TITLE: Using Orienteering to Examine the Interactions of Exercise and Cognitive Training on Human Cognition and Brain-Derived Neurotrophic Factor

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ABSTRACT

Exercise enhances aspects of human cognition, but its intensity may matter. Recent research in animal models suggests that vigorous exercising may be optimal as it releases greater amounts of lactate, which in turn, activates brain-derived neurotrophic factor (BDNF) in the hippocampus to support cognitive function. Furthermore, the effects of exercise on cognition may be augmented when exercise is combined with cognitive training. The sport of orienteering simultaneously combines exercise with spatial navigation and therefore may result in greater cognitive benefits than exercising only, especially when performed at a vigorous intensity. Therefore, the aim of the present study was to examine the effects of an acute bout of orienteering at different intensities compared to exercising only on cognition and BDNF. We hypothesized that vigorous-intensity orienteering would increase lactate and BDNF and improve cognition more than moderate-intensity orienteering, or vigorous exercise alone. To test this, we recruited 63 recreationally active, healthy young adults (M_{age} = 21.10±2.75 years) with no orienteering experience. The orienteering groups navigated a 1.3km orienteering course while exercising at either a vigorous (80-85% of HRR) or moderate (40-50% of HRR) intensity. The control group exercised at a vigorous intensity on the same course without navigation. Peak lactate, heart rate and rating of perceived exertion during the intervention were used to verify exercise intensity. Immediately before and after the intervention, serum BDNF was extracted, and cognitive function was assessed using the Mnemonic Similarity Task for high-interference memory and the Groton Maze Learning Test for spatial learning and memory. The results show that exercising (M = 5.35±2.52 mmol/L) and orienteering (M = 5.94±2.49) at a vigorous intensity elicited greater peak lactate levels than orienteering at a moderate intensity (M = 2.01±1.20). Vigorous exercise (p = .003) and orienteering (p = .043) elicited greater increases in BDNF, and

individuals with higher peak lactate had greater increases in BDNF (r_s (56) = .28, p = .037). Vigorous exercise also benefited high-interference memory compared to moderate orienteering (p = .019). All groups increased in spatial learning (p*'s* < .05*)*, but only the vigorous orienteering group improved in delayed spatial memory performance (p = .007). Overall, the results provide evidence for the beneficial effects of combined exercise plus navigation training interventions for spatial cognitions that are closely related to the process engaged during cognitive training.

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LIST OF ABBREVIATIONS

AD	Alzheimer's Disease
ANOVA	Analysis of Variance
BBB	Blood-Brain Barrier
BDNF	Brain-Derived Neurotrophic Factor
CBF	Cerebral Blood Flow
ELISA	Enzyme-Linked Immunosorbent Assay
FNDC5	Fibronectin Type III Domain-Containing Protein 5
GMLT	Groton Maze Learning Test
GPS	Global Position System
HR	Heart Rate
HR_{Max}	Maximum Heart Rate
HRR	Heart Rate Research
LDI	Lure Discrimination Index
LT	Lactate Threshold
M_{ex}+O	Moderate-Intensity + Orienteering Group
MAPE	Mean Absolute Percentage Error
MST	Mnemonic Similarity Task
NSQ	Navigational Strategy Questionnaire
PASB-Q	Physical-Activity and Sedentary Behavior Questionnaire
PCG1-a	PPARG Coactivator 1-alpha
REC	Recognition Memory
RHR	Resting Heart Rate
RPE	Rating of Perceived Exertion
SAM	Survey of Autobiographical Memory
SD	Standard Deviation
SEM	Standard Error of the Mean
SIRT1	Silent Information Regular 1
TrkB	Tropomyosin-related kinase B
V_{ex}+O	Vigorous-Intensity + Orienteering Group
V_{ex}	Vigorous Exercise Group
VO_2Max	Maximum rate of oxygen consumption

DECLARATION OF ACADEMIC ACHIEVEMENT

Emma Waddington's role:

- Obtained ethics approval with the Hamilton Integrated Sciences Research Board.
- Designed study protocol and selected measures.
- Developed standard operating procedure for study.
- Set up study materials for data collection.
- Trained and supervised undergraduate research students and volunteers who assisted with data collection.
- Led data collection (including blood draws), analysis (including ELISA), and interpretation.
- Responsible for manuscript preparation

Role of co-authors:

- JH assisted EW with ethics application.
- JH assisted EW with selection of study measures and of protocol design.
- JH assisted EW with data interpretation.
- JH obtained study funding.

Introduction

Alzheimer's Disease (AD) and related dementia disorders are the sixth leading cause of death worldwide (Rayathala et al., 2022), affecting over 55 million people and causing severe neurodegeneration that impairs cognition and compromises independent living. Age is the greatest risk factor for dementia, and as the world's population ages, dementia rates are predicted to climb sharply to affect over 152 million people by 2050 (Nichols et al., 2022). Unfortunately, there is no known cure for dementia and therefore, preventative measures that can help to stave off age-related cognitive decline are essential. Exercise has been recognized as one of the most important modifiable lifestyle factors for preventing dementia and mitigating dementia-related cognitive decline across the lifespan (Ruegsegger & Booth, 2018). Evidence suggests that physical inactivity can increase the risk of dementia as much as genetics (Fenesi et al., 2017) and that the risk of developing dementia in later life is 1.92 times more likely in those with low aerobic fitness levels in midlife (Kurl et al., 2018). Together, these findings suggest that early interventions that increase aerobic-based physical exercise are key for cognitive function. However, the optimal type of exercise for boosting cognition is less definite. Evidence in older adults suggests that vigorous exercise may be optimal for promoting memory performance (Kovacevic et al., 2020) and that the effects may be enhanced when exercise is simultaneously combined with a cognitively challenging activity (Bo et al., 2019). However, the research on this topic in younger adults remains sparse, especially regarding acute interventions. Therefore, the present study aimed to use the sport of orienteering, which simultaneously combines exercise with navigation, to evaluate the acute effects of aerobic exercise at various intensities with or without a simultaneous cognitive challenge in young adults.

Engaging in aerobic exercise induces a multitude of effects that can impact cognitive function, including increases in cerebral blood flow to various brain regions (Chapman et al., 2013; Endo et al., 2013), and heightened neurotransmitter activity (Vecchio et al., 2018). The present thesis focuses on specific changes related to human hippocampal function with the ultimate goal of identifying early interventions for preventing dementia.

The Hippocampus as a Target for Exercise-Related Protection

While most regions of the human brain are susceptible to subtle levels of atrophy across adulthood without incurring cognitive deficits (Long et al., 2012), the hippocampus is widely reviewed as a highly vulnerable brain region to age-related neurodegeneration (Burke & Barnes, 2006). Atrophy of the hippocampus declines at an annual rate of 1.12% in those over 70 years old, compared to 0.38% for those under age 55 (Fraser et al., 2015). In AD, these rates are even more severe, reaching atrophy rates of just under 4% (Jack et al., 1998). This accelerated atrophy of the hippocampus can cause severe impairments to the cognitive functions it mediates including memory and spatial processing (Deweer et al., 1995). Consequently, early interventions that can mitigate this hippocampal atrophy are crucial.

Research demonstrates that physical exercise interventions increase neuroplasticity in the hippocampus to offset its atrophy (Firth et al., 2018). In non-human animal models, aerobic exercise in the form of voluntary wheel running promotes neurogenesis in the dentate gyrus of the hippocampus in mice (van Praag et al., 1999). In humans, aerobic exercise interventions of walking or jogging that improve fitness also result in an increase in hippocampal blood flow (Maass et al., 2015) which have also been associated with improvements in critical hippocampal functions such as memory (Chapman et al., 2013). In one study, older adults who walked three times per week for a year experienced a 2 percent increase in hippocampal volume (Erickson et

al., 2011). Another study found similar volumetric increases in younger adults who exercised for four months (Frodl et al., 2020). Importantly, while there is extensive evidence for the *chronic* exercise effects on hippocampal function (Colcombe & Kramer, 2003; Hillman et al., 2008; Smith et al., 2010), there is also evidence for the effect of *acute* exercise on cognitive function such that the acute effects of exercise (alone, or the accumulation of) have the potential to stimulate neural adaptations that support hippocampal-dependent functioning (Chang et al., 2012).

BDNF as a Mediator of Exercise Effects in the Hippocampus

Brain-derived neurotrophic factor (BDNF) is a neurotrophin protein that supports neurogenesis by promoting the health, survival and functionality of neurons in the brain (Miranda et al., 2019). Across various brain structures, BDNF is most abundant in the hippocampus, but its abundance declines with aging and AD (Connor et al., 1997; Erickson et al., 2010). Rodents endowed with the pathological features of AD have marked reductions in BDNF within the hippocampus (Silhol et al., 2005) and impaired spatial memory (Schaaf et al., 2001). In humans, circulating BDNF extracted from serum samples is lower in older adults than younger adults and has been associated with poorer performance on various cognitive tests (Forlenza et al., 2010; Shimada et al., 2014) including severe episodic memory difficulties in AD patients (Peng et al., 2005).

Exercise may promote cognition through the activation of BDNF (Walsh & Tschakovsky, 2018). An acute bout of aerobic exercise increases circulating BDNF in young adults (Griffin et al., 2011), healthy older adults (Håkansson et al., 2016), and older adults with AD (Coelho et al., 2014), and higher intensities of exercise yield greater BDNF gains (Griffin et al., 2011; Jeon & Ha, 2017; Shah et al., 2022). However, following the cessation of exercise, BDNF levels fall

within 30 to 60 minutes (Walsh & Tschakovsky, 2018). However, in the brief period following acute exercise when BDNF is elevated, its upregulation is believed to ready the brain for the neuroplastic changes needed to support learning and memory (Loprinzi et al., 2019). For example, one study found that BDNF and cognition increase more when exercise preceded cognitive training compared to when exercise followed cognitive training (Nilsson et al., 2020). Importantly, it is the repeated activation of BDNF following each acute exercise bout that is believed to underlie benefits such as increases in hippocampal volume that are observed with chronic interventions (Erickson et al., 2011; Firth et al., 2018). Although these exercise-related increases in BDNF are not isolated to the hippocampus and have been found in regions such as the prefrontal and perirhinal cortex of rats (Hopkins & Bucci, 2010; Uysal et al., 2015), the increases observed in the hippocampus are most important in the context of AD and dementia prevention.

The L-lactate Pathway

Although many putative mechanisms are at play (Pedersen, 2019), emerging evidence identifies a potential link between BDNF expression and the accumulation of l-lactate (Cai et al., 2022; Hashimoto et al., 2021; Müller et al., 2020). Briefly, l-lactate, the most abundant of two lactate enantiomers and herein referred to as lactate, is a product of pyruvate metabolism under anaerobic conditions and accumulates in the muscle during vigorous exercise (Hashimoto et al., 2018). Once considered as a metabolic waste product (Passarella et al., 2008), it is now understood that is taken up by the brain as a fuel source during vigorous exercise (Ide et al., 2000), and, that lactate has roles in activating BDNF-mediated neuroplasticity (El Hayek et al., 2019; Hashimoto et al., 2018; van Hall et al., 2009). After being transported from the muscle through the blood and across the blood-brain barrier, lactate accumulates in brain regions

including the hippocampus where it participates in various signalling cascade pathways (e.g., the SIRT1 to PGC1α to FNDC5 pathway) (Pedersen, 2019) that increase BDNF and improve hippocampal functions like spatial learning and memory (El Hayek et al., 2019). One fast-acting mechanism of action occurs when BDNF binds to its receptor, tropomyosin-related kinase B (TrkB), which promotes long-term potentiation of existing neural synapses to enhance neuroplasticity in a matter of minutes and thus, is a potential mechanism that may underlie the acute effects of exercise (Müller et al., 2020).

Furthermore, lactate levels are reduced in the hippocampi of animal models of AD (Lu et al., 2015) but injections of lactate into the hippocampus of rats have shown to increase performance on hippocampal-dependent spatial memory (Newman et al., 2011). Consequently, interventions like high-intensity exercise that increase the production of lactate in muscle may be a viable strategy for supporting neuroplasticity across the lifespan due to its roles as both a fuel source to the brain and as an activator of BDNF (El Hayek et al., 2019; Ide et al., 2000; Müller et al., 2020). However, to date, only a few studies have examined the impact of lactate on hippocampal-dependent cognition in humans (Hashimoto et al., 2018; Kujach et al., 2020), and therefore, more work is needed.

Insights into the role that lactate may play in BDNF signalling are predominantly from exercise interventions that manipulate intensity. Increases in exercise intensity cause the accumulation of lactate in the muscle. At high intensities, lactate can increase past the lactate threshold (LT) which can occur around ~ 4mmol/L of lactate in untrained adults, and after which its accumulation increases exponentially (Faude et al., 2009; Heck et al., 1985). Higher intensity training also increases BDNF (Griffin et al., 2011; Shah et al., 2022) and memory to a greater extent in both younger (Jeon & Ha, 2017) and older adults (Kovacevic et al., 2020), compared to

moderate-intensity exercise. Specifically, intense exercise can be performed as high-intensity interval training (HIIT), and one study compared the acute effect of HIIT (10 one-minute bouts of exercise at 90% of maximal workload followed by one minute of active recovery) versus moderate-intensity continuous training (MICT; 20 minutes at 70% of maximal workload) and found that HIIT increased BDNF more than MICT (Marquez et al., 2015), suggesting that it is the *peak* intensity of exercise rather than its duration that may be most important for activating BDNF and improving memory.

In this way, accumulated lactate from acute bouts of vigorous exercise has the potential to build up to chronic adaptations in cognitive function. Yet, as previously mentioned, many studies to date have not directly measured lactate and BDNF, and instead, indirectly quantify lactate through the manipulation of exercise. Therefore, the role of lactate in muscle-to-brain signalling in humans is promising but lacks significant supporting evidence.

The Effects of Exercise on Hippocampal Cognitive Functions

Although exercise enhances many different aspects of human cognition, its direct effects on hippocampal neuroplasticity are associated with improvements in performance on hippocampal-dependent processes including spatial and episodic memory, among others.

Spatial Memory

Beneficial changes in hippocampal-dependent spatial memory have been well documented following exercise interventions (Erickson et al., 2009). For example, among previously sedentary older adults who engaged in 12 weeks of progressive treadmill walking/running, those who experienced greater increases in aerobic fitness had better spatial object recall and recognition (Maass et al., 2015). Similarly, in older adults with probable mild cognitive impairment, engagement in 12 weeks of aerobic exercise training improved their

ability to memorize spatial locations compared to non-active controls (Nagamatsu et al., 2013). These results are important as degeneration of the hippocampus with aging and AD is associated with deficits in spatial memory capacity including the ability to encode, store and retrieve information about spatial locations, landmarks, and their relations (Ekstrom & Hill, 2023). In non-human animal models, performance on the Morris Water Maze Task was reduced in rodents endowed with AD's pathological features compared to healthy rodents (Lu et al., 2015). In this task, animals are placed into a circular pool of water sectioned into quadrants (North, South, East, and West). The animals cannot see into the water and so they must learn to navigate to a target platform from different quadrants using distal cues as directly as possible (Vorhees & Williams, 2006). Human analogs of the Morris Water Maze have been created in which older adults perform worse than younger adults (Newman & Kaszniak, 2000). Moreover, older adults also have poorer performance than younger adults on mental rotation tasks as revealed by both an increased time to encode and mentally rotate images (Hertzog & Rypma, 1991). Increased rate of error and decreased efficiency on the Groton Maze Learning Test which examines hippocampal spatial learning and memory have also been seen in older adults compared to their younger counterparts (Pietrzak et al., 2007)

Episodic Memory

Episodic memory includes the ability to encode and retrieve memories of past personal events that contain spatial and temporal information about the event (Tromp et al., 2015). Deficits in episodic memory are caused by age- and AD-related hippocampal atrophy (Gorbach et al., 2017), and are among the first symptoms to appear in AD (Burgess et al., 2002). Specifically, deficits in encoding episodic memories are common in older adults, compared to their younger counterparts (Tromp et al., 2015). Chronic exercise interventions, however,

improve episodic memory across the lifespan (Nouchi et al., 2014; Ruscheweyh et al., 2011). Among older adults with a heightened genetic risk for AD, those who engaged in more physical activity have better episodic memory (Ferencz et al., 2014).

Although the processes of spatial memory and episodic memory are typically evaluated using separate tasks, there is a strong interplay between the two. Spatial memory provides a framework for episodic memory by denoting *where* a particular event took place and an associative link forms between the two that can aid in the retrieval of either (Lugtmeijer et al., 2019; Robin et al., 2018). According to the *Associative Deficit Hypothesis*, older adults may have difficulty connecting the different components of a specific memory, and without these key associations, episodic memory and/or spatial memory encoding and retrieval may also be impaired (Naveh-Benjamin et al., 2004). Consequently, spatial memory impairments can contribute to episodic memory deficits and vice versa, as is seen with aging and AD (Burgess et al., 2002; Konishi & Bohbot, 2013).

A related hippocampal-dependent memory process that is particularly sensitive to exercise-induced improvements is the ability to distinguish between highly similar memories, known as high-interference memory, which is believed to be dependent on neuroplasticity within the dentate gyrus of the hippocampus to form distinct memories (Bakker et al., 2008; Becker, 2017). The Mnemonic Similarity Task (MST) is a modified object recognition task that tests one's ability to resolve high-interference memories (Stark et al., 2019). In the MST, participants are shown images of everyday items and must correctly identify a shown image as *old* (identical to a previously studied image), *similar* (similar, but not exactly the same as a previously studied image), or *new* (different than a previously studied image). The ability to correctly identify an image as *similar* indicates better high-interference memory performance (Bakker et al., 2008;

Kirwan & Stark, 2007; Yassa & Stark, 2011). Older adults have poorer high-interference memory performance than younger adults (Bakker et al., 2008; Kirwan & Stark, 2007; Yassa & Stark, 2011) whereas exercise interventions improve high-interference memory performance in both younger (Déry et al., 2013; Heisz et al., 2017) and older adults (Kovacevic et al., 2020) even after a single acute bout (Callow et al., 2022).

Enhancing the Effects of Exercise on Hippocampal Cognitive Functions with Combined Training

Combining exercise with a cognitively challenging task (or, in rodent models, an enriched environment) may add to the cognitive effects of exercise (Miyamoto et al., 2018; Zhu et al., 2016). In the process of neurogenesis, exercise and cognitive training work through two complementary pathways. Evidence from animal models suggests that exercise predominantly impacts the proliferation of newborn neurons in the dentate gyrus whereas cognitive training predominantly impacts the maturation and survival of those newborn brain cells (Kronenberg et al., 2003). For example, animals that engaged in 10 days of voluntary wheel running and then lived in an enriched environment had more newborn neurons in the dentate gyrus than animals who were either exposed to exercise or enrichment only (Fabel et al., 2009).

In humans, the technology does not exist to count the number of newborn neurons that proliferate and survive; however, there is evidence to suggest that *sequentially* combining exercise with cognitive training can improve cognition more than either training program alone. For example, in young adults, exercise responders to six weeks of HIIT experienced greater improvements in high-interference memory when the exercise was combined with a memory training task than when it was not (Heisz et al., 2017). Additionally, older adults with vascular cognitive impairment had better mental rotation and forward digit-span performance following

12 weeks of combined exercise-cognitive training than exercise or cognitive training only (Bo et al., 2019). Similar findings have been seen in older adults with mild cognitive impairment and at risk for dementia (Ngandu et al., 2015; Styliadis et al., 2015).

There is also evidence to suggest that the efficacy of combined interventions may be greater when exercise and cognitive training are performed *simultaneously* (Gavelin et al., 2021). A recent meta-analysis comparing single modality interventions to those that combined exercise and cognitive training found that simultaneous intervention had larger effect sizes for improving cognitive function (*SMD* = .43, 95% CI [0.27, 0.60]) than sequential interventions (*SMD* = .34, 95% CI [0.21, 0.47]) or interventions which used cognitive training alone (*SMD* = .32, 95% CI [0.16, 0.49]; Gavelin et al., 2021). Furthermore, protocols that combine spatial navigation tasks with treadmill walking were noted to be particularly effective at improving navigation and mental rotation performance in older adults, compared to walking only (Lövdén et al., 2012). While intriguing, the mechanisms underlying these augmentative effects in humans are lacking. Moreover, no study to date has manipulated exercise intensity and examined whether increases in lactate and BDNF are related to the extent to which combined training improves cognition.

Orienteering as a Combined Exercise and Cognitive Training Intervention

The sport of orienteering naturally and simultaneously integrates exercise with spatial navigation and therefore may be an optimal way to target hippocampal plasticity and function. In orienteering, the athlete's objective is to navigate through a series of checkpoints across an unknown terrain as fast as possible using only a topographical map and a compass (Eccles et al., 2002). Through focused attention and quick deduction of key information, highly skilled orienteers demonstrate the use of favourable visual strategies when examining complex

topographical maps (Liu, 2019) and are better able to synthesize and simplify that information for use during spatial navigation (Eccles et al., 2002, 2006).

Expertise in orienteering involves spatial navigation, which is a critical function of the hippocampus that subserves one's ability to use spatial information and mental representations of an environment to move through space (Ekstrom & Hill, 2023). Atrophy of the hippocampus in old age impairs spatial navigation, reduces motility (Burns, 1999), and increases dementia risk (Ritchie et al., 2018). Advanced hippocampal degeneration in AD renders the hippocampus unable to create, store, or use mental maps for wayfinding (Serino & Giuseppe, 2014), causing disorientation even in familiar environments, a condition known as topographical disorientation (Boccia et al., 2019; Moffat & Resnick, 2002). Therefore, orienteering may be a useful intervention strategy to prevent navigational decline.

Certain navigational strategies rely heavily on spatial information that is processed either via a third-person allocentric frame or a first-person egocentric reference frame (Byrne et al., 2007; Serino & Giuseppe, 2014). Of these navigational strategies, allocentric spatial processing is the most reliant on the hippocampus, and therefore also susceptible to impairment with age and AD (Colombo et al., 2017; Ekstrom et al., 2003; Nedelska et al., 2012). Age-related impairments in the allocentric reference frame can interrupt one's ability to switch between allocentric and egocentric frames of reference for spatial processing which is essential for efficient navigation (Grön et al., 2000; Harris et al., 2012; Wang & Spelke, 2002). This may be where orienteering can help; expert orienteers read a map (an allocentric perspective) on the run and can quickly update their location on a map based on their first-person view of the terrain (an egocentric perspective) which engages rapid translations of spatial information between an allocentric and an egocentric reference frame (Eccles et al., 2006).

Specifically, allocentric representations relate objects to an external reference landmark, unrelated to the individual's location. For example, those navigating using an allocentric strategy may see a map from a birds-eye view and navigate using a series of turns using cardinal directions or distances. Because allocentric processing is reliant on the hippocampus, it often diminishes with age, and it is well documented that these changes can contribute to the inability to create or store mental maps within this brain region (Colombo et al., 2017; Ekstrom et al., 2003; Nedelska et al., 2012). It is noted that otherwise healthy middle-aged adults who are at risk for dementia have reduced allocentric spatial processing skills compared to those without risk factors for dementia (Ritchie et al., 2018).

In contrast, when navigating using an egocentric spatial processing reference frame, the location of objects depends on the individual's location (relative to the self). Those using egocentric spatial processing to navigate see themselves in the first-person, and primarily use left or right decisions related to their current location. Mediated by the posterior parietal lobe (Colombo et al., 2017; Cook & Kesner, 1988), egocentric spatial processing abilities are spared throughout the aging process, and older adults tend to adopt this type of spatial navigation more (Moffat et al., 2006; Rodgers et al., 2012).

According to the "use it or lose it" hypothesis (McKinlay, 2016), orienteering may help delay age-related impairments in wayfinding. One study on healthy adults aged 18-87 years old found that orienteering experts reported greater use of both allocentric and egocentric spatial navigation compared to non-orienteering controls who heavily relied on procedural landmark navigation (Waddington & Heisz, 2023). Although orienteers report greater feelings of pleasure when exploring new areas than non-orienteers (Feraco et al., 2021), suggesting that they may be self-selecting into the sport, a recent review by Ekstrom and Hill suggests that spatial navigation

may be developed over time and with experience (Ekstrom & Hill, 2023). This may be why orienteers with intermediate skill level were no different than controls in spatial navigation tendencies (Waddington & Heisz, 2023), and relied more on a third navigational strategy, procedural navigation, which does not involve spatial information, and instead is based on rote memorization and the ability to recall verbal or written directions (Ramanoël et al., 2020; Zhong & Kozhevnikov, 2016).

Furthermore, orienteering may help to prolong hippocampal functioning across the lifespan. Expert orienteers reported better spatial memory than novices regardless of their age (Waddington & Heisz, 2023). Moreover, expert orienteers with more than eight years of experience were better able to mentally rotate 3D objects than non-orienteering controls, and both expert and beginner orienteers with less than five years of experience demonstrate superior visualization abilities than non-orienteers (Feraco et al., 2021). In a 12-week training study, college students who completed orienteering training had greater improvements in spatial memory than those who completed badminton training (Bao et al., 2022). Notably, these results were only significant in the male participants. However, in a two-week training intervention, both male and female students who completed six consecutive days of racing in a virtual orienteering video game improved their 3D mental rotation abilities and performance on various spatial processing tasks (Roca-González et al., 2016), suggesting that a few acute orienteering sessions may be enough to improve spatial cognition.

There are three reasons why orienteering may be an effective stimulator of neuroplasticity. The first is related to its evolutionary semblance to hunter-gatherer activities that were dependent on the integration of spatial memory and navigation with locomotion to find food. As the human brain evolved to perform tasks which combine physical exercise with

various spatial processing challenges, theories suggest that the brain is more receptive to such activities (Kempermann et al., 2010; Raichlen & Alexander, 2017). The second reason is a case of "use it or lose it". Modern-day dependencies on vehicles for transport and passive navigation guided by Global Positioning Systems (GPS) cause most humans to underutilize their wayfinding abilities, leading to spatial memory deficits (Dahmani & Bohbot, 2020) and reduced sense of direction (Ishikawa, 2019) which orienteering has the potential to rescue. The third and final reason is that orienteering typically involves vigorous intermittent exercise, which (as reviewed above) seems especially good for promoting hippocampal plasticity and function through mechanisms such as increased lactate and BDNF. However, to date, no study has examined the effects of an acute bout of orienteering on hippocampal-dependent memory, lactate, and BDNF at different exercise intensities.

Purpose

The purpose of this study was to examine the effects of orienteering at different exercise intensities (vigorous versus moderate) compared to vigorous intermittent exercise only, on hippocampal-dependent memory and BDNF. We hypothesized that the vigorous-intensity interventions would increase lactate more than the moderate-intensity intervention, resulting in a greater increase in BDNF, high-interference memory and spatial learning and memory. Because of the potential for exercise-cognitive training interactions, we also hypothesized that orienteering at a vigorous exercise intensity would elicit larger gains in BDNF and memory compared to orienteering at a moderate intensity or just vigorous exercise alone. Finally, as an exploratory analysis, we examined whether navigational efficiency would differ when orienteering at a vigorous versus moderate intensity.

Methods

Participants

Participants were 63 (n = 41 female, 65.1%) healthy young adults (M_{age} = 21.10, SD = 2.75, range = 18-30) who were recruited to the study using self-referral based on the criteria of being aged 18-30 years old and being recreationally active (as confirmed by the Physical Activity and Sedentary Behaviour Questionnaire [PASB-Q] – outlined below). Participants were screened to ensure eligibility using the following criteria: 1) no diagnosis of a neurological disorder or major health condition using self-report, 2) English language fluency, 3) no colour blindness, 4) engagement in the sport of orienteering from zero to a maximum of 5 times. Written informed consent was obtained through an online questionnaire. Participants were randomized into one of three groups: 1) moderate-intensity orienteering (M_{ex}+O) (n = 22), 2) vigorous-intensity orienteering (V_{ex}+O) (n = 21) and 3) vigorous-intensity exercise (V_{ex}) (n = 20), as described below. Participants received a $30 CAD honorarium for their time. This study was reviewed and approved by the Hamilton Integrated Research Ethics Board (#14560) prior to recruitment and data collection.

Sample Size Calculation

In the current body of literature, evidence for an additive effect of acute combined exercise-cognitive interventions on BDNF and cognitive function is limited, especially in young adults. As such, the sample size calculation for the present study was based on the expected exercise-induced effects on BDNF (d = 1.10) (Miyamoto et al., 2018) and high-interference memory performance (η_p^2 = 0.13) (Heisz et al., 2017) in young adults from similar, chronic interventions. Using G*Power (Bartlett, 2022) calculations for a three-group mixed ANOVA design, a sample size of 30 was required to determine significant changes in BDNF following exercise (d = 1.10, α = .05 and power = .80), and a sample size of 54 was required to observe

significant changes in cognitive function (η_p^2 = 0.13, α = .05 and power = .80). Therefore, a target of recruiting at least 54 participants was set. Additionally, we aimed to explore the interactions of acute exercise and cognitive training, but given the limited research, this was merely exploratory.

Materials and Procedure

A number generator was used to randomly assign participants to one of three groups: 1) moderate-intensity orienteering (Mex+O), 2) vigorous-intensity orienteering (Vex+O), or 3) vigorous-intensity exercise (Vex).

Baseline Measurements

Online Questionnaire. Following randomization and before the in-lab session, participants completed an online questionnaire (LimeSurvey software) to collect demographic information including age, biological sex, education level, previous and current McMaster student status, level of familiarity with the McMaster campus, previous and current sports participation, type and frequency of video game engagement, and previous engagement in orienteering (Appendix A).

All participants then completed the Physical Activity and Sedentary Behaviour Questionnaire (PASB-Q; Appendix B) from the Canadian Society for Exercise Physiology (Canadian Society for Exercise Physiology, 2013). Total weekly moderate-to-vigorous aerobic exercise engagement was calculated from the PASB-Q by multiplying the average number of active days by the average length of activity time (minutes/week).

Participants' baseline navigational tendencies were assessed using the Navigational Strategy Questionnaire (NSQ; Zhong & Kozhevnikov, 2016). Using a 5-point Likert scale, participants rated 44 items corresponding to three different navigational strategies: allocentric

spatial processing, egocentric spatial processing, and procedural processing, as previously outlined. For each strategy, an average score was calculated (Appendix C).

Baseline autobiographical memory was assessed using the Survey of Autobiographical Memory (SAM; Palombo et al., 2013). In the SAM, subjective memory is assessed across 26 items which are answered using a 5-point Likert scale. Each item is weighted and summed appropriately to obtain an average for four domains of memory including episodic, spatial, semantic, and future memory. In this study, we examined episodic and spatial memory specifically (Appendix D).

In-lab Measurements. In the lab, prior to the intervention, the participant's height, weight, and waist circumference were measured by a trained researcher. Participants were instructed to remove shoes and stand with their heels and head touching the wall as height was measured to the nearest half-centimetre. Weight (without shoes) was recorded in kilograms (kg) using an electronic scale. Measures of waist circumference were taken from the anterior-superior iliac spine upon exhalation.

Resting heart rate (RHR) was determined using a wetted Polar HR-10 chest heart rate (HR) monitor synchronized to a Polar Pacer Pro watch (Polar Electro, Kempele, Finland). The lowest HR value recorded in the final two minutes of a 12-minute supine resting period was used. Maximum heart rate (HR_{Max}) was estimated using the equation $HR_{Max} = 208 - (0.7 * RHR)$.

Exercising heart rate zones for each group were determined using the percent of heart rate reserve (HRR) and the equation $(HR_{Max} – RHR) * (intensity) + RHR$. For the M_{ex}+O group, exercise intensity was calculated as 40-50% of HRR, and 80-85% of HRR was used for the V_{ex}+O and V_{ex} groups.

Estimates of VO_2 peak were calculated using the *WorldFitnessLevel.org* website (Nes et al., 2011). Participants were asked to respond to the website questions as accurately as possible and input their anthropometric and HR measurements, as described above (Appendix E).

Intervention Measurements of Exercise Intensity

Heart rate. While heart rate was collected continuously throughout the intervention course using the Polar HR-10 monitor, values were recorded at the midpoint and finish of the intervention course, as well as 10 minutes post-intervention. The highest of these recorded values was analyzed as the peak HR level.

Rating of Perceived Exertion (RPE). The Borg Scale for rating of perceived exertion (RPE; Borg, 1982) was used to gauge perceived exercise intensity and was measured pre- and post-intervention, as well as at the midpoint and finish of the intervention course. Participants were asked to point to and communicate the level of physical exertion they were experiencing on a scale from 6 (no exertion) to 20 (maximal exertion). As RPE is highly related to HR, measures of RPE confirmed the level of exercise intensity was appropriate for each participant and their exercise condition (Appendix F). The highest of these recorded values was analyzed as the peak RPE level.

Blood lactate. A Lactate Plus portable analyzer and test strips (Nova Biomedical, Waltham, MA) were used to determine blood lactate from whole blood. Participants were instructed to sanitize the tip of their third or fourth finger with an alcohol swab, and a drop of blood was obtained using a blood-lancing device. After wiping off the first drop of blood, a second drop of blood was collected onto the test strip and measured using the Lactate Plus device. Of the recorded values taken prior to and post-intervention as well as at the midpoint and finish of the intervention course, the highest value was analyzed as the peak lactate level.

Pre/Post Intervention Measurements

Prior to the intervention, cognitive testing was completed before obtaining a serum sample for BDNF. Following the intervention, the blood sample was collected within 10 minutes of finishing the intervention course and was followed by cognitive testing.

Blood Sample for BDNF. Three-hour fasted samples of venous blood were obtained from a vein in the antecubital fossa before and immediately after the intervention to quantify levels of serum BDNF. Samples were collected into BD Vacutainer SST tubes (BD, Franklin Lakes, NJ), chilled on ice, allowed to clot for a minimum of 45 minutes following sample collection and then centrifuged at 1000 x g for 15 minutes at 4°C. For all samples, 300µL of supernatant was collected to obtain serum and aliquoted into microtubes and stored immediately at -20°C until analysis. The concentration of serum BDNF was quantified using a sandwich Biosensis Mature BDNF Rapid^{TM} ELISA Kit (Biosensis Pty Ltd, Thebarton, Australia). Samples were diluted 100x, and both samples and standard were run in duplicate. Using a BioTek SynergyMx spectrophotometer, absorbance was measured at 450 nm and analyzed using Gen 5 1.11 Software (BioTek Instruments Inc., Winooski, VT). Following this analysis, select samples whose concentration fell above the standard curve were re-analyzed using a 125x dilution and the same protocol.

High-Interference Memory. High-interference memory was tested using Kirwan and Stark's Mnemonic Similarity Task (MST; Bakker et al., 2008; Kirwan & Stark, 2007; Yassa & Stark, 2011). The MST consists of an incidental study phase, followed immediately by a test phase (Figure 1a). In the study phase, participants are shown a series of images of 60 everyday objects displayed on the screen for two seconds and participants must classify whether the image is an 'indoor' or an 'outdoor' item. In the test phase participants are shown 20 'repeat' images

(correct response = "Old"), 20 'lure' images that are highly similar but not identical to a previous image (correct response = "Similar"), and 20 completely new, 'foil', images (correct response = "New"), and asked to classify them. The ability to correctly classify 'lure' items as "similar" indicates high interference memory and is termed the "lure discrimination index" (LDI) and was calculated as [*p* ("Similar" | Lure image) – *p* ("Similar" | Foil image)] × 100. General recognition memory (REC) was defined as the ability to correctly label a 'repeat' image as "old", [*p* ("Old" | Repeat image) − *p*("Old" | Foil image)] × 100.

The MST was administered before and after the intervention with different stimulus sets, and the order of each set was counterbalanced.

Spatial learning and memory. A computerized version of the Groton Maze Learning Test (GMLT), adapted from the Milner Maze (Milner, 1964), was used to assess hippocampal spatial learning and memory (Schroder et al., 2004). The 2D maze consists of a 28-step pathway, hidden beneath a 10x10 grid of grey tiles that is revealed by clicking on the matrix squares using a mouse (Figure 1b). Participants are instructed that they can only select adjacent tiles and cannot move diagonally or jump across tiles. If a correct tile in the sequence is selected, then the tile briefly turns green, a rewarding auditory tone is played, and the participant can proceed to select a new tile in the sequence. If an incorrect tile is selected, the tile briefly turns red, an incorrect auditory signal is played, and the participant must click on the previously correct tile before selecting a new tile. In the learning phase, participants complete the same maze five times in a row and are instructed to complete the maze as fast as they can. After a 10-minute break, participants complete the same maze a sixth and final time to test delayed memory.

The maze efficiency index (Pietrzak et al., 2007) was used to quantify learning and memory performance by taking the number of correct moves per second in each learning phase

and dividing by the total time of the trial, normalized using a logarithmic base 10 transformation. In the learning phase, mean maze efficiency was calculated by averaging across the five trials. This GMLT was administered before and after the intervention with different maze sequences randomized using the computer software.

The Intervention

Practice Phase. Following pre-intervention measures, all participants completed a six-checkpoint, 500m outdoor familiarization course on the McMaster campus to warm up for exercise and to become accustomed to their experimental condition. All participants were taught how to read their HR on the Polar Pacer Pro GPS watch and were instructed how to maintain their pace such that their HR remained in the target range.

Participants in the orienteering groups (M_{ex}+O, V_{ex}+O) were explained an orienteering map legend and were taught how to orient their map in relation to the terrain and use it to plan a route and locate checkpoints. Participants were taught strategies to re-locate themselves should they make an error. With the help of a researcher, participants located the first three checkpoints at a light walking pace of 30-40% of HRR. For the fourth checkpoint, participants were encouraged to locate the checkpoint without advice from the researcher. For the final two checkpoints, participants located the checkpoints on their own at their target intensity (moderate-intensity: 40-50% of HRR) or running (vigorous-intensity: 80-85% of HRR) pace.

Participants in the V_{ex} group followed a researcher around the 500m course, beginning at a walking pace of 30-40% of HRR for the first 4 checkpoints, and at their target intensity of 80-85% of HRR for the final two checkpoints.

Intervention Phase. Immediately after the practice phase, all participants were led to the start location by a researcher, and the Polar Pacer Pro GPS watch was started to track the

participant's HR and route. Then, all participants completed the intervention course around the McMaster University campus according to their intervention condition.

The intervention course was approximately 1.3 kilometres and consisted of 10 checkpoints marked by distinctive pin flags. Before commencing data collection, an in-lab validation of the Polar Pacer Pro GPS watch was performed. The most efficient route along the intervention course (as deemed by an expert orienteer) was measured using a count-metre in both a forward and reverse direction, for a total of six measures. The Polar Pacer Pro GPS watch uses GPS + GLONASS satellites with a 1-second sampling rate, and using two separate Polar Pacer Pro watches, two different researchers walked and ran the most efficient route in the forward and reverse directions. By comparing the average course distance based on the count metre values and watch values, the mean absolute percentage error (MAPE) for each watch was < 2% (Appendix G).

Those in the V_{ex} group exercised at a vigorous intensity (80-85% of HRR) but did not engage in orienteering. Instead, a member of the research team led the participant along the most efficient route. In contrast, those in the orienteering groups *navigated* to the checkpoints using the map at either a moderate (40-50% of HRR) or vigorous intensity (80-85% of HRR) along any route they chose. For safety reasons, a researcher silently followed participants during the intervention. For participants who were severely lost or who had ventured outside the bounds of the orienteering map, the researcher informed them of their current location to ensure their safety but did not provide any additional information that would alter their navigational decisions.

All participants were responsible for tracking their HR at each checkpoint and were instructed to adapt the pace or pause (until their HR returned to the target zone, for a maximum

of 1 minute) at a checkpoint to remain within the target HR zone. At the midpoint and finish locations, a second researcher recorded HR, RPE and blood lactate.

Data Analysis

All data were analyzed using SPSS (IBM SPSS Statistics for Macintosh, version 28.0; IBM Corp., Armonk, NY). For all study variables, descriptive statistics were computed. Normality was assessed using skewness, kurtosis and visual inspection of histograms. Data were screened for outliers using visual inspection of boxplots. For BDNF, cases were removed if BDNF concentration was above the standard curve, in which seven cases were removed (M_{ex}+O = 1, V_{ex}+O = 4, V_{ex} = 2). For the MST, two cases were removed as the difference in the percent corrected and raw score for appropriate key use in the MST was >8% (M_{ex}+O = 2, V_{ex}+O = 1). Cases were also removed due programming errors with the cognitive tests (MST: M_{ex}+O = 1, V_{ex}+O = 1; GMLT: M_{ex}+O = 1, V_{ex}+O = 1) and because of errors in GPS data recording (V_{ex}+O = 2). Only complete cases were analyzed. All tests were computed with $\alpha = .05$ and a 95% confidence interval.

Potential Covariates

One-way analysis of variance (ANOVA) was used to assess group differences in all demographic variables, weekly physical activity, predicted VO_2Max, campus familiarity, weekly video game engagement, orienteering engagement, spatial navigation tendencies and autobiographical memory as well as pre-intervention differences in BDNF and cognition.

Manipulation Checks

To ensure that our intervention was adequate in reaching the desired exercise intensity, three separate one-way ANOVA tests were computed for peak HR, peak RPE and peak blood lactate between groups. For blood lactate, a Kruskal-Wallis Means Ranks Test was used to

confirm that the proportions of those above or below their lactate threshold differed by group, thus indicating that our intervention was adequate in reaching the desired exercise intensity.

Primary Outcome Variables

Primary outcome variables included BDNF, high-interference memory (MST LDI), recognition memory (MST REC) and spatial learning and memory (GMLT learning and test efficiency). These variables were analyzed using separate 2 x 3 mixed model ANOVAs with a within-subjects factor of time (pre, post) and between-subjects factor of group (M_{ex}+O, V_{ex}+O, V_{ex}). A *priori* one-sample *t*-tests (one-tailed) were computed to evaluate the pre- to post-intervention increases in BDNF and memory for each group with Hedge's correction. Post hoc analyses used a Bonferroni correction. Spearman's correlation was used to evaluate the relationship between peak lactate and the percent change in BDNF.

Secondary Outcome Variables

An exploratory analysis was done to quantify differences in the navigational performance of the two orienteering groups. The distance travelled by each of the orienteering groups (M_{ex}+O, V_{ex}+O) was compared to the V_{ex} group which, by design, travelled the most efficient route. A 2 x 3 mixed model ANOVA with a within-subjects factor of course half (start to midpoint, midpoint to finish) and between-subjects factor of group (M_{ex}+O, V_{ex}+O, V_{ex}) was used to identify group differences in distance travelled as indicated by the Polar Pacer Pro GPS watch. Post hoc analyses used a Bonferroni correction. Spearman's correlation was used to determine existing associations between the total distance travelled and subjective measures of spatial processing/navigation and memory for the two orienteering groups.

Results

Participants

Potential Covariates

Table 1 reports descriptive statistics of key baseline variables across groups. Ninety-two percent (n = 58/63) of participants were students at McMaster University. Participants did not differ in pre-exercise measures of high-interference or recognition memory, or in spatial learning and memory, however, pre-intervention BDNF levels were higher for the M_{ex}+O group than the V_{ex}+O or V_{ex} groups ($p < .001$) (Table 2). Univariate ANOVA tests confirmed no other baseline differences between groups (Table 1).

Intensity Manipulation Checks

Our intervention successfully induced the appropriate level of exercise intensity for each group, as confirmed by a significant main effect of group for peak lactate ($F(2, 60) = 17.49$, $p < .001$, $\eta^2 = .37$), peak RPE ($F(2, 60) = 21.56$, $p < .001$, $\eta^2 = .42$) and peak HR ($F(2, 60) = 57.26$, $p < .001$, $\eta^2 = .66$). Post hoc comparisons indicate that the M_{ex}+O group had lower peak HR, peak RPE and peak lactate than the V_{ex}+O and V_{ex} groups which did not differ from each other (Figure 2). Peak HR was within the instructed range of 40-50% of HR_{Max} for the moderate-intensity group and 80-85% of HR_{Max} for both vigorous-intensity groups. Furthermore, the proportion of participants above the estimated LT of 4mmol/L differed significantly between groups ($H(2) = 21.70$, $p < .001$), with more participants above the LT in the V_{ex}+O and V_{ex} groups than the M_{ex}+O group (Figure 3).

Primary Outcome Variables

BDNF

Fifty-six complete cases were analyzed (M_{ex}+O: n = 21, V_{ex}+O: n = 17, V_{ex}: n = 18). The mixed model ANOVA revealed a significant main effect of time ($F(1, 53) = 10.51$, $p = .002$, η_p^2

= .17) and group ($F(2, 53) = 10.15$, $p < .001$, $\eta_p^2 = .28$), but no interaction. Figure 4 shows an increase in BDNF for all groups over time, but the change was only significant for the V_{ex}+O ($t(16) = 1.83$, $p = .043$, $g = .42$) and the V_{ex} groups ($t(17) = 3.09$, $p = .003$, $g = .70$) but not the M_{ex}+O group ($t(20) = 1.43$, $p = .08$, $g = .30$).

Across groups, post-hoc analysis revealed lower BDNF values for the V_{ex} group which were lower at baseline and post-intervention (Table 2) and differed significantly from the M_{ex}+O ($p < .001$), and the V_{ex}+O ($p = .02$) groups (Figure 4b). Therefore, it is assumed that these group differences reflect baseline differences that are unrelated to the intervention.

Importantly, figure 5 depicts the results from the Spearman's correlation, whereby the percentage change in BDNF was significantly correlated to the peak lactate achieved during exercise ($r_s(56) = .28$, $p = .037$).

High-Interference and Recognition Memory

Fifty-eight cases were included in the analysis (M_{ex}+O: n = 19, V_{ex}+O: n = 19, V_{ex}: n = 20). For high-interference memory captured by the LDI, there was a significant group by time interaction ($F(1, 55) = 3.23$, $p = .047$, $\eta_p^2 = .11$). As shown in figure 6, high-interference memory performance improved for the V_{ex}+O and V_{ex} groups but declined for the M_{ex}+O group, and the difference between the M_{ex}+O and V_{ex} groups was significant ($t(37) = -2.45$, $p = .019$, $g = -.77$). There were no other effects for high-interference memory and no effects or interaction for recognition memory (Table 2).

Spatial Learning and Memory

Sixty-one complete cases were analyzed (M_{ex}+O: n = 21, V_{ex}+O: n = 20, V_{ex}: n = 20). Both the learning and delayed test trials revealed a significant main effect of time (learning: $F(1, 58) = 30.39$, $p < .001$, $\eta_p^2 = .35$; test: $F(1, 58) = 8.09$, $p = .006$, $\eta_p^2 = .12$) indicating that all

groups improved in spatial processing efficiency (Table 2). For learning trials, figure 7a depicts a significant improvement in performance for all groups following the intervention, though the largest effect size was for the V_{ex}+O group ($t(19) = 4.11$, $p < .001$, $g = .88$), followed by the V_{ex} group ($t(19) = 3.43$, $p = .001$, $g = .74$), and the M_{ex}+O group ($t(20) = 2.14$, $p = .022$, $g = .45$). On delayed test performance (Figure 7b), only the V_{ex}+O group improved significantly ($t(19) = 2.70$, $p = .007$, $g = .58$,). There was no effect of group or interaction for either the learning or delayed test trials.

Secondary Outcome Variables

Course Distance

Sixty-one complete GPS cases were analyzed (M_{ex}+O, n = 22, V_{ex}+O, n = 19, V_{ex}, n = 20). The mixed model ANOVA for distance travelled revealed a significant main effect of group ($F(2, 58) = 8.81$, $p < .001$, $\eta_p^2 = .23$) such that the orienteering groups travelled longer (M_{ex}+O: $p = .018$; V_{ex}+O: $p < .001$) than those in the non-orienteering group, but the orienteering groups did not differ ($p = .51$). Distances travelled can be found in Table 3. Figure 8 depicts the extra distance travelled by the two orienteering groups compared to the most efficient route.

Across participants in the orienteering groups, those who travelled farther, and by extension made more errors, reported significantly worse egocentric spatial processing tendencies from the NSQ ($r_s(41) = -.44$, $p = .004$) and subjective spatial memory from the SAM ($r_s(41) = -.44$, $p = .004$). Though not significant, allocentric spatial processing trended in the same direction ($r_s(56) = -.27$, $p = .086$). In contrast, procedural spatial processing ($r_s(41) = -.13$, $p = .438$) and subjective episodic memory ($r_s(41) = .05$, $p = .744$) were not related to the total distance travelled (Table 4).

Discussion

The present study was the first to examine the effects of an acute bout of orienteering versus exercise on cognition in a sample of healthy young adults who were recreationally active but unfamiliar with orienteering. The results revealed a strong effect of exercise intensity such that vigorous-intensity exercise elicited greater increases in lactate, BDNF and memory. Furthermore, vigorous orienteering improved spatial learning and memory more than vigorous running, suggesting an additional benefit of simultaneous training.

This is one of the first human studies to examine the effects of exercise intensity and lactate on BDNF and hippocampal-dependent memory and adds important insights to this emerging body of research that has been predominantly done in animal models. Of the several pathways that may underlie the beneficial effects of vigorous exercise on BDNF and cognition, lactate has been identified as a prime candidate (Pedersen, 2019). In line with this hypothesis, our vigorous exercise interventions led to higher peak lactate levels alongside greater increases in BDNF and better memory than our moderate-intensity intervention. Furthermore, participants who achieved higher peak lactate during the intervention had greater percent increases in BDNF following the intervention. This suggests a link between the accumulation of lactate during vigorous exercise and a subsequent increase in BDNF, and these findings are in line with animal research and minimal human research which indicate the mediating role of lactate in increasing BDNF to support hippocampal functions (El Hayek et al., 2019; Hashimoto et al., 2018; van Hall et al., 2009). However, it is important to acknowledge that our vigorous exercise intervention resulted in system-wide changes, of which lactate is only one of many factors affected; alongside increases in lactate, we also observed the expected increases in HR and RPE. Therefore, to test the specific role of lactate in the promotion of BDNF and cognition, infusion studies that increase lactate in the absence of a physiological stress response are needed.

Because of prior research showing augmented cognitive effects following combined exercise-cognition interventions (Heisz et al., 2017; Lövdén et al., 2012; Ngandu et al., 2015; Styliadis et al., 2015), we had expected vigorous orienteering to also increase BDNF more than vigorous running alone, but it did not in this intervention. Although this contrasts with our hypothesized outcome, it is in line with prior work in younger adults who report no additional benefits from exercise-cognitive training on BDNF (Heisz et al., 2017; Miyamoto et al., 2018). BDNF is thought to respond to energetic challenges (Marosi & Mattson, 2014), and given that our sample consisted of healthy young adults who were recreationally active, the additional challenge of running while navigating may not have been enough of an acute energetic demand, especially since the average time to complete the course was only 12 minutes and the wayfinding task was through a familiar terrain. Future work should examine the potentially additive effects of orienteering compared to running on BDNF using longer-duration training interventions and less familiar terrains.

We also expected vigorous orienteering to improve cognition more than vigorous running, however, this was not the case for high-interference memory. Instead, high-interference memory (LDI) improved to a similar extent for both vigorous groups, suggesting that this aspect of cognition is more sensitive to the acute effects of exercise intensity than it is to the combined effects of exercise and cognitive training experienced during an acute bout of orienteering. Although the effects of vigorous exercise on high-interference memory were expected and consistent with prior work (Crawford & Loprinzi, 2019; Déry et al., 2013; Heisz et al., 2017; Kovacevic et al., 2020), the decrement in high-interference memory following moderate-intensity orienteering was not expected. Perhaps, since vigorous exercise has been shown to increase BDNF to a greater extent than moderate exercise (Griffin et al., 2011; Jeon & Ha, 2017;

Shah et al., 2022), those orienteering at a moderate intensity had reduced neurogenic support which rendered these substrate-dependent memory benefits unobtainable. However, this was not the case for spatial learning and memory.

Spatial learning and memory were tested using the GMLT, which is a close 2D analog to the 3D wayfinding of orienteering. Although all groups increased in spatial learning efficiency, suggesting an overlap in the neural pathways primed by vigorous exercising and navigation, only the vigorous orienteering group increased in performance for the delayed test. This suggests that the neural pathways involved in delayed retrieval may be primed even more than spatial learning when vigorous exercise and navigation are combined. Importantly, the delayed spatial memory test was the only cognitive test that improved more for vigorous exercise combined with orienteering than vigorous exercise alone, and it is important to consider why. The most likely explanation relates to the cognitive processes engaged during the delayed test, which engaged spatial memory after a 10-minute delay, and therefore is highly dependent on the hippocampus (Byrne et al., 2007). Notably, deficits in spatial memory are one of the earliest impairments associated with neurodegeneration of the hippocampus in AD (Boccia et al., 2019; Burns, 1999; Moffat & Resnick, 2002). The engaged cognitive processes may also be the reason why the added benefits of vigorous orienteering versus vigorous exercise were only observed in spatial memory tested by the GMLT, and not high-interference memory tested by the MST, suggesting that the additional benefits from this combined task may be stronger for tasks that are more closely related to the cognitive demands of orienteering. This hypothesis follows from prior work that has examined other cognitive training interventions and noted a greater benefit for near-transfer tasks (i.e. tasks that depend on similar cognitive processes to the cognitive training) than far-transfer tasks (i.e. tasks that depend on different cognitive processes than the cognitive

training) (Sala et al., 2019a; Sala et al., 2019b). The also results hint at how orienteering may impact hippocampal function, especially when considered in light of classic research on London taxi drivers. Compared to controls, the taxi drivers had larger *posterior* hippocampi and the size of their posterior hippocampi correlated with years of experience; however, the taxi drivers had smaller *anterior* hippocampi than controls suggesting a trade-off between the two that is in line with the "use it or lose it" model (Maguire et al., 2000). Critically, the posterior hippocampus is involved in visuospatial cognition, including the ability to locate an object within a particular space. In comparison, the anterior hippocampus is involved in non-spatial cognition, including object-based conceptual information (Sheldon & Levine, 2016; Vogel et al., 2020). Might orienteering improve spatial memory at the cost of other memory? Our prior work suggests not, given that expert orienteers reported significantly better spatial memory than intermediate-level orienteers or non-orienteers controls but did not differ in their subjective episodic memory (Waddington & Heisz, 2023). However, future research is needed to understand whether orienteering experience causes a shift in the ratio of posterior-to-anterior hippocampal volume.

In terms of spatial processing and navigation, previous work indicates that expert orienteers use both egocentric and allocentric spatial processing to a greater extent and with more flexibility between the two than controls that rely heavily on procedural navigation (Waddington & Heisz, 2023). Expert orienteers also make more frequent glances between the orienteering map and the terrain when navigating compared to those with less experience (Eccles et al., 2006) which would allow them to quickly transition between egocentric and allocentric viewpoints. In comparison to expert orienteers (Waddington & Heisz, 2023) the novices tested in this study reported more reliance on procedural navigation and less reliance on allocentric navigation. Although the participants in the present study were predominantly McMaster University students

with high familiarity with the campus on which the orienteering course was set, both orienteering groups travelled significantly farther, and by extension made more errors than the most efficient route. However, some participants made fewer errors than others, as revealed by the individual differences in distance travelled. Those who travelled shorter distances reported greater reliance on egocentric spatial navigation and reported better spatial memory skills. These results align with past work showing that expert orienteers rely on more robust spatial representations for successful navigation and wayfinding (Waddington & Heisz, 2023) and also suggest a range of competency in these spatial processing abilities in young, healthy adults who had no orienteering experience prior to this study.

Surprisingly, allocentric spatial navigation was not significantly related to course distance travelled. This is surprising since prior research found allocentric spatial processing, like egocentric spatial processing and spatial memory, to be associated with expertise in the sport of orienteering (Waddington & Heisz, 2023). Lack of allocentric navigation may also be explained by overreliance on GPS, which minimizes active navigation and the practice of allocentric navigation in a case of "use it or lose it" (Dahmani & Bohbot, 2020) and may be used more commonly by those with little experience in orienteering as allocentric navigation may require more practice to be developed (Ekstrom & Hill, 2023). Females also tend to rely less on allocentric navigation than males (Grön et al., 2000) and our sample was predominantly female. Or, alternatively, the lack of association with allocentric spatial processing and navigational efficiency may have been a consequence of participants' familiarity with the course, which was laid out on the highly familiar terrain of the university campus. In this case, a greater reliance on spatial memory and egocentric navigation may be expected and sufficient. For example, rather than recurrently updating their location on the map using allocentric processing, participants

could identify campus buildings by their name and then navigate based on previously learned, first-person views of campus to the checkpoint locations. Regardless, future work should examine how the reliance on different navigational strategies changes with training in orienteering over time.

Limitations

As the first known study to date to examine the effects of an acute bout of orienteering on cognition and BDNF, this study makes important advances in the field of exercise cognition but is not without its limitations. One limitation of this study is the high proportion of McMaster students included in our sample who had high familiarity with the University campus and therefore navigating through the orienteering course may not have been a sufficient cognitive challenge to induce changes in BDNF. While exercising on campus provided a safe environment for orienteering, navigational tendencies may differ between familiar and unfamiliar terrains (Ekstrom & Hill, 2023), and future work should examine the orienteering interventions in unfamiliar terrains over a variety of course difficulties.

Moreover, we were underpowered to examine sex-based differences in the relationships between lactate, BDNF and cognition following acute orienteering interventions. As noted above, males and females approach navigation in different ways (Grön et al., 2000). Furthermore, there is evidence that females have lower BDNF responsivity to acute exercise (Dinoff et al., 2017) and lower performance gains in spatial memory tasks following orienteering training than males (Bao et al., 2022). Females also tend to have lower lactate responses at the same relative exercise intensity compared to males, suggesting that lactate-induced BDNF activation from exercise may impact males and females differently (Wheatley et al., 2014).

Therefore, our results may not be generalizable to all populations, and future work should consider examining these sex-based effects.

Finally, this study examined the efficacy of orienteering in providing beneficial changes in cognitive function and BDNF in young adults only but did not include older adults. Although early interventions that target hippocampal function are critical for dementia prevention, the lack of older adults included in this study means that the results may not be generalizable to interventions for older adults or individuals with AD. While this study provides the groundwork regarding the safety and efficacy of acute bouts of orienteering in young adults, future work is needed in older adult populations.

Future Directions

As one of the first studies to examine the impact of an acute bout of orienteering on hippocampal-dependent memory function, this study provides important groundwork for future interventions to examine the effects of orienteering on brain health and function.

First, by demonstrating the efficacy of using orienteering for improving cognition in younger adults, future work should test the effects of orienteering in both acute and long-term training interventions in other populations. Given the prominent spatial memory deficits that occur with age and AD (M. C. Newman & Kaszniak, 2000), orienteering may be especially beneficial for these populations.

Comparing methods for extracting BDNF is another important area for future work. Commonly in human studies, circulating BDNF can be measured in the blood through samples of serum, plasma, or BDNF bound in platelets. While serum concentrations of BDNF are the most measured in studies, and contain more BDNF than plasma samples (Walsh & Tschakovsky, 2018), exercise and cognitive training may impact serum and plasma levels of BDNF differently.

There is evidence that plasma BDNF increases following exercise, cognitive training and combined interventions, whereas serum BDNF increases following exercise or combined interventions, but not after cognitive training alone (Tarassova et al., 2020). Moreover, how BDNF is measured may also be sensitive to exercise intensity such that small increases in serum or plasma BDNF occur following light exercise and are likely driven by BDNF in platelets, but exercise at higher intensities can induce much larger increases in serum and plasma BDNF (Gibbons et al., 2023). Future work should include measures of serum, plasma, and BDNF found in platelets to fully describe the neurogenic effects of orienteering.

Finally, as noted above, future research should use unfamiliar terrains for creating orienteering courses to ensure a sufficient cognitive challenge and to capture the use of different navigational strategies without the influence of learned routes. Together, implementing orienteering training interventions in this way may provide insight into how the reliance on different navigational strategies may change as a function of orienteering training.

Conclusion

This study demonstrates the effect of vigorous exercise on lactate, BDNF and hippocampal-dependent memory. The added effects of orienteering over exercise were only observed at a vigorous intensity and on spatial memory, suggesting an overlap in the neural pathways primed by vigorous exercise and navigation that can benefit cognitive processes that were “exercised” by the cognitive training task. Overall, the important groundwork from this study suggests that orienteering may be an effective way to boost spatial processing abilities that typically decline with aging and AD.

Table 1. Descriptive Statistics Between Intervention Groups

	Moderate Exercise + Orienteering (M_{ex}+O)	**Vigorous Exercise + Orienteering (V_{ex}+O)**	**Vigorous Exercise (V_{ex})**
n	22	21	20
Age (years)	20.48 ± 2.34	21.76 ± 3.36	21.05 ± 2.46
Age Range (years)	18 - 28	18 - 30	18 - 26
Sex (F/M)	14/8	13/8	14/6
Height (cm)	170.16 ± 7.52	166.79 ± 8.53	169.40 ± 9.30
Weight (kg)	67.38 ± 10.53	68.91 ± 12.64	63. 91 ± 14.89
WC (cm)	82.52 ± 7.15	83.80 ± 7.72	81.97 ± 10.17
Aerobic Physical Activity (min/week)	172.74 ± 91.12	172.62 ± 99.64	198.25 + 103.76
Predicted VO_2Max (mL/kg/min)	49.23 ± 6.58	50.19 ±6.23	48.95 ± 5.51
Education			
< Secondary	0%	0%	5%
Secondary	82%	57%	75%
Post-Secondary	18%	24%	5%
Post-Graduate	0%	19%	15%
McMaster Student (No/Yes)	1/21	2/19	2/18
McMaster Campus Familiarity (%)			
Not Familiar	5%	5%	5%
Somewhat Familiar	0%	5%	15%
Neutral	41%	24%	20%
Fairly Familiar	32%	29%	25%
Very Familiar	23%	38%	35%
Orienteering Engagement (%)			
None	77%	90%	80%
1-2 times	18%	5%	15%
3-4 times	5%	5%	5%
Video Games (hours/week)			

None	55%	62%	55%
<1 to <3	27%	24%	30%
3 to <7	14%	10%	15%
7 to <9	5%	5%	0%
NSQ			
Egocentric	3.34 ± 0.72	3.09 ± 0.61	3.02 ± 0.84
Allocentric	3.12 ± 0.65	2.97 ± 0.61	2.85 ± 0.79
Procedural	3.65 ± 0.47	3.64 ± 0.55	3.58 ± 0.68
SAM			
Episodic	100.68 ± 15.51	100.54 ± 12.32	102.53 ± 14.07
Spatial	98.21 ± 12.91	96.10 ± 14.01	97.10 ± 12.72

Note: Values reflect M ± SD. WC = waist circumference, NSQ = Navigational Strategy Questionnaire, SAM = Survey of Autobiographical memory.

Table 2. Mean Pre- and Post-Intervention Values for Primary Variables

	Moderate Exercise + Orienteering (M_{ex}+O)	**Vigorous Exercise + Orienteering (V_{ex}+O)**	**Vigorous Exercise (V_{ex})**
n	19	19	20
REC			
REC Pre (%)	87.89 ± 10.46	87.47 ± 8.02	85.20 ± 12.67
REC Post (%)	84.84 ± 9.95	85.21 ± 11.57	84.15 ± 11.91
LDI			
LDI Pre (%)	49.89 ± 26.22	47.68 ± 17.08	45.10 ± 22.27
LDI Post (%)	42.37 ± 30.01	49.95 ± 18.55	52.20 ± 19.82
GMLT Learning Efficiency			
Learning Efficiency Pre (%)	26.12 ± 10.32	23.28 ± 6.85	24.60 ± 5.89
Learning Efficiency Post (%)	29.45 ± 7.88	29.42 ± 6.45	29.92 ± 4.52
GMLT Test Efficiency			
Test Efficiency Pre (%)	35.69 ± 14.24	30.62 ± 9.69	34.19 ± 10.68
Test Efficiency Post (%)	38.32 ± 11.07	36.24 ± 9.61	38.42 ± 9.23
n	21	17	18
BDNF			
Pre BDNF (ng/mL)	40.96 ± 10.15*	38.85 ± 9.30	29.00 ± 6.19
Post BDNF (ng/mL)	42.33 ± 9.75	39.78 ± 8.71	31.33 ± 5.39

Note: Values reflect M ± SD. REC = Recognition Memory (MST), LDI = Lure Discrimination Index (MST), GMLT = Groton Maze Learning Test. * = $p < .05$.

Table 3. Distances Travelled on the Intervention Course Between Groups

	Moderate Exercise + Orienteering (M_{ex}+O)	**Vigorous Exercise + Orienteering (V_{ex}+O)**	**Vigorous Exercise (V_{ex})**
n	22	19	20
Average Distance Start to Midpoint (m)	678.18 ± 136.40	718.42 ± 130.74	606.5 ± 13.09
Average Distance Midpoint to Finish(m)	681.82 ± 38.62	697.37 ± 57.24	641.00 ± 13.34
Average Total Distance (m)	1360 ± 149.83*	1415.79 ± 162.25***	1247.50 ± 17.73

Note: Values reflect M ± SD. * = $p < .05$ compared to V_{ex} group, ** = $p < .01$ compared to V_{ex} group, *** = $p < .001$ compared to V_{ex} group.

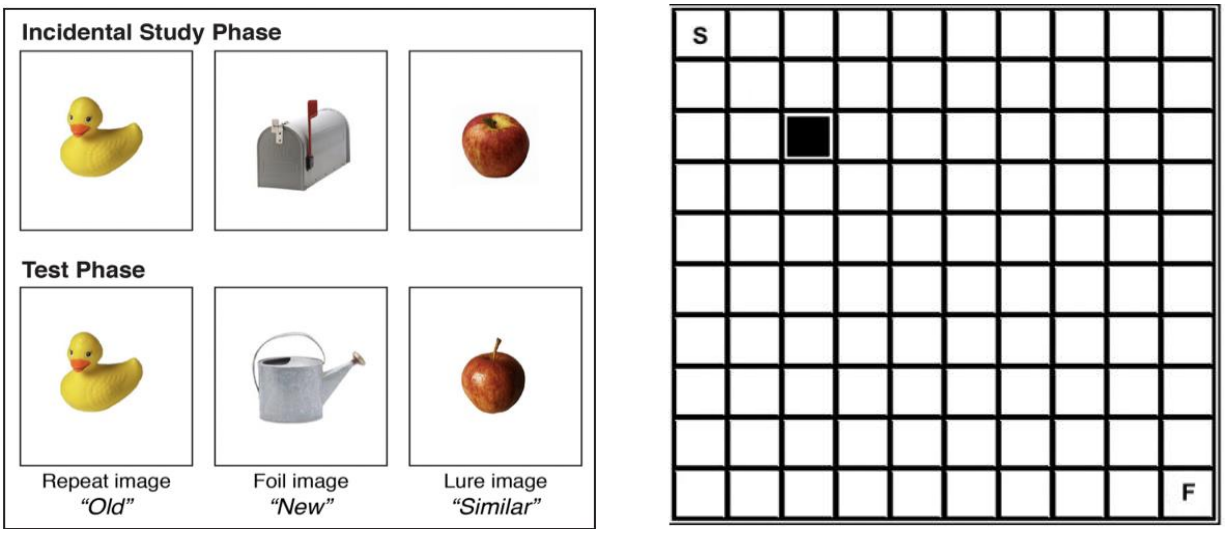
Table 4. Correlation Matrix Between Distance Travelled in the Intervention Course by the Orienteering Groups and Subjective Measures

	1	**2**	**3**	**4**	**5**	**6**
1. Total Distance (m)	-					
2. NSQ Egocentric	-.44 **	-				
3. NSQ Allocentric	-.27	.55 ***	-			
4. NSQ Procedural	-.13	-.32 *	-.02	-		
5. SAM Episodic	-.05	.06	-.11	-.14	-	
6. SAM Spatial	-.44 **	.59 ***	.49 ***	-.26	-.11	-

Notes: NSQ = Navigational Strategy Questionnaire; SAM = Survey of Autobiographical Memory. * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

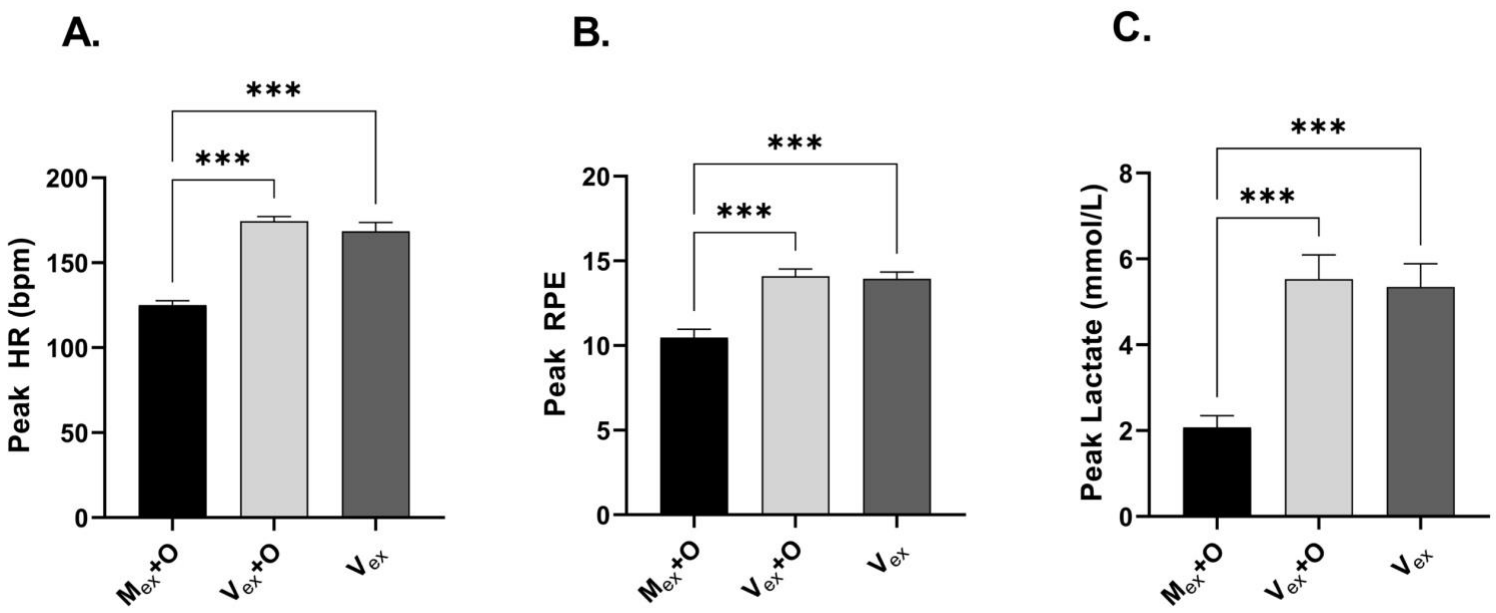
Figure 1. Cognitive Measures

A) **B)**



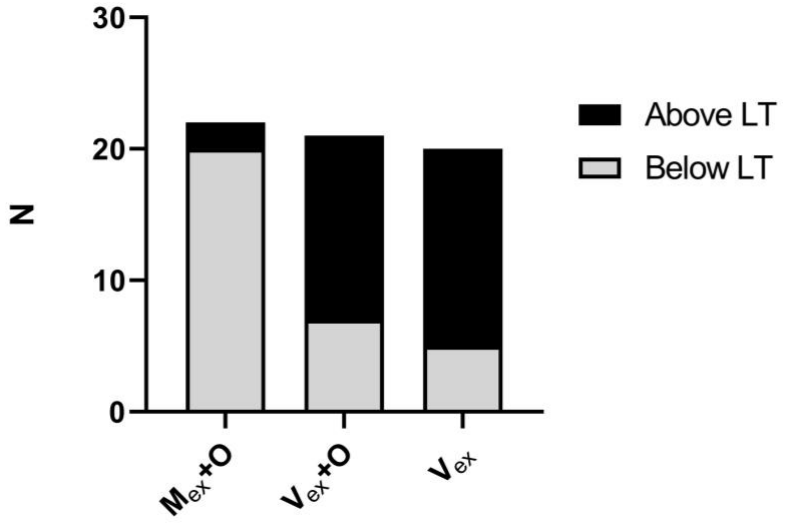
Notes: A) A depiction of the Mnemonic Similarity Task. In the incidental study phase, 60 everyday items are learned, and are categorized as 'indoor' or 'outdoor' items. In the test phase, participants must determine if the images shown are the same as in the test phase (20 repeat, or 'old' images), similar, but not exactly the same (20 lure, or 'similar' images), or completely novel (20 foil, or 'new' images). B) The Groton Maze Learning Test involves navigating up, down, left, or right through a 28-step maze from start (S) to finish (F), hidden below a grey 10x10 grid. For each correct move, the tile briefly turns green, and an auditory cue is given, allowing participants to continue. If the move is incorrect, an auditory cue is given and the tile will briefly turn red, in which participants must click back on the previously correct square to continue. Participants learn the maze over five learning trials and are tested once following a 10-minute delay period.

Figure 2. Group Differences in Exercise Intensity Metrics



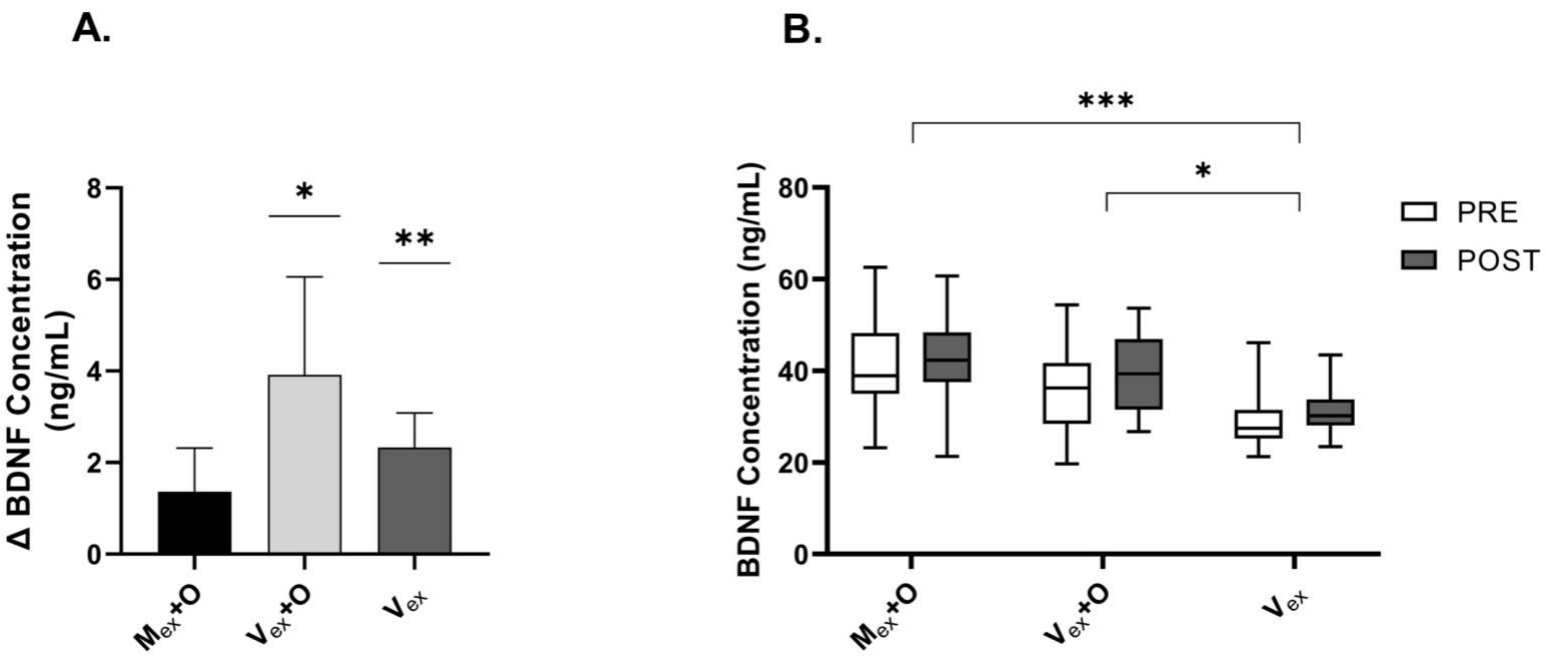
Notes: Bars reflect mean score, and error bars reflect ± SEM. *** = $p < .001$.

Figure 3. Proportion of Intervention Group Above or Below Lactate Threshold



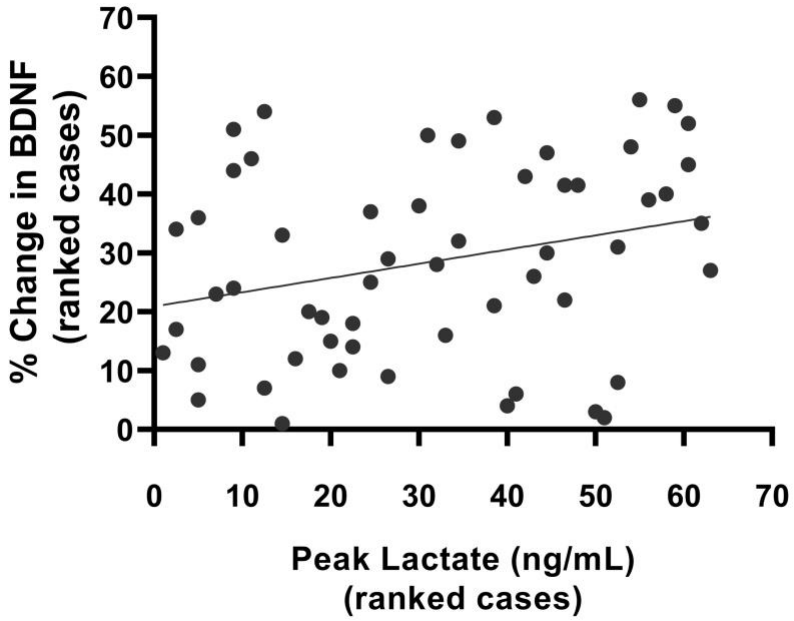
Notes: Values reflect peak level of blood lactate achieved during the intervention.

Figure 4. Change in BDNF Concentration and Group Differences Following Intervention



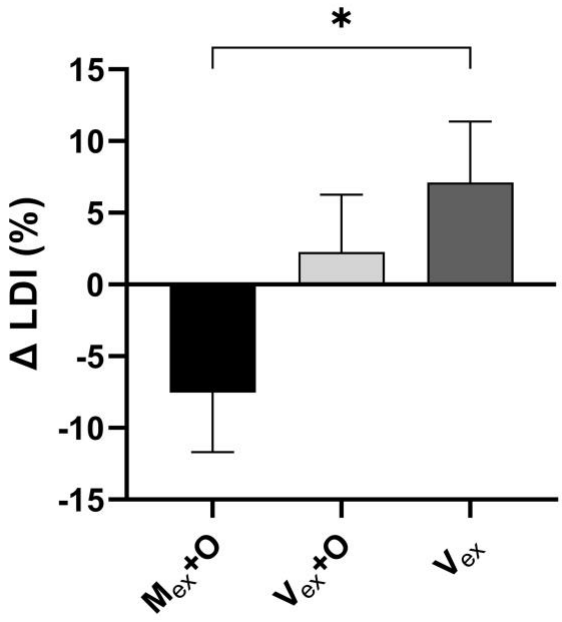
Notes: A) Mean change (± SEM) in BDNF concentration between groups. B) A boxplot showing the interquartile range, median, minimum, and maximum concentration of BDNF between groups from pre- to post-intervention * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Figure 5. Correlation Between Peak Lactate and Relative Percent Change in BDNF



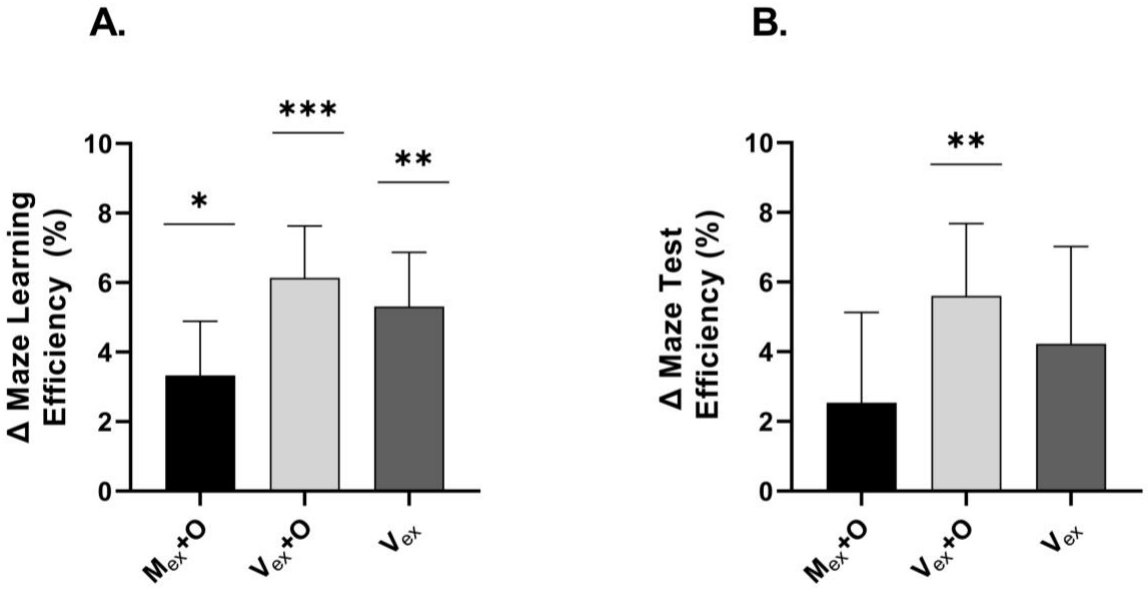
Notes: A scatterplot of ranked cases showing the correlation between the relative percent change in BDNF, and the peak lactate achieved during exercise. $Y = 0.242x + 20.89$, $R^2 = .078$.

Figure 6. Change in High-Interference Memory (LDI) Following Intervention



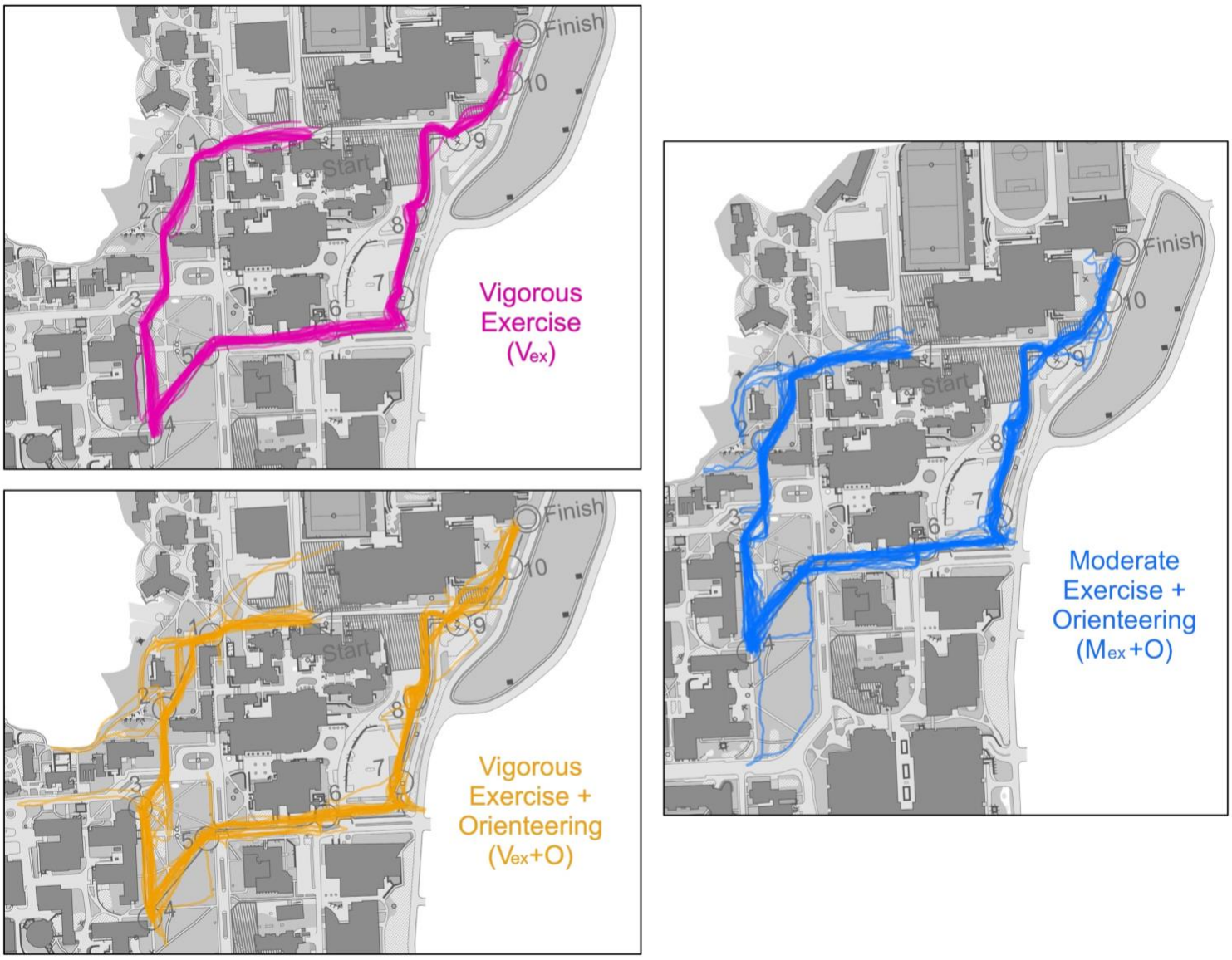
Notes: Mean change (± SEM) in LDI performance on the MST between groups. * = $p <$ .05.

Figure 7. Change in Spatial Learning and Memory Following Intervention



Notes: A) Mean change (± SEM) in GMLT learning efficiency between groups. B) Mean change (± SEM) in GMLT test efficiency between groups. * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Figure 8. Routes Traversed on the Intervention Course Between Groups



Notes: Figures show the routes traversed by each study group along the (approximately) 1.3km intervention course around the McMaster University campus. Routes in pink show the paths of those in the V_{ex} group (n = 20) who followed a researcher throughout the course at a running speed. These pink routes indicate the most efficient route. Routes in yellow show the paths of the V_{ex}+O group (n = 19) who actively navigated the intervention course at a running speed. The blue routes are those in the M_{ex}+O group (n = 22) who navigated the intervention course at a running speed. All routes were tracked using a Polar Pacer Pro GPS watch. Note that all participants started and finished in the same location, and checkpoints remained in the same location for all trials; any major differences in routes, such as a different starting location (seen in V_{ex}+O group map) can be attributed to GPS accuracy.

Appendix A. Sample demographics questions.

3. Have you participated in any sports in the past? If so, please list what sports you took part in.
   Type answer

4. Do you currently participate in any sports? If so, please list what sports you take part in.
   Type answer

5. How many hours of video games do you play a week?
   a. None
   b. Less than 1 hour
   c. 1 to <3 hours
   d. 3 to <5 hours
   e. 5 to <7 hours
   f. 7 to <9 hours
   g. > 9 hours
   h. Prefer not to answer
   i. Other (please specify how many hours) ____.

6. If you play video games, please list the types of video games you play. Otherwise, type N/A.
   Type answer

9. On a scale from 1-5, how familiar would you say you are with the McMaster Campus?
   a. 1 (not very familiar)
   b. 2
   c. 3
   d. 4
   e. 5 (very familiar)

10. How many times have you done orienteering in the past?
    a. None
    b. 1
    c. 2
    d. 3
    e. 4
    f. 5
    g. More than 5.

Appendix B. CSEP Physical Activity and Sedentary Behaviour Questionnaire (Canadian Society for Exercise Physiology, 2013)

Please answer the following questions based on what you do in a typical week.

1. Aerobic Physical Activity:
   Frequency: In a typical week, how many days do you do moderate-intensity (like brisk walking) to vigorous-intensity (like running) aerobic physical activity?
   Type answer

2. Aerobic Physical Activity:
   Time/Duration: On average, for days that you do at least moderate-intensity aerobic physical activity (as specified above), how many minutes do you do?
   Type answer

3. Perceived Aerobic Fitness:
   In general, would you say that your aerobic fitness (ability to walk/run distances) is:
   a. Excellent
   b. Very good
   c. Good
   d. Fair
   e. Poor

Appendix C. Sample questions from the Navigational Strategy Questionnaire (Zhong & Kozhevnikov, 2016).
This survey concerns the common habits or techniques that you engage in when navigating the familiar places in your everyday environment. When filling out this questionnaire, please TAKE YOUR TIME, THINK CAREFULLY, and be VERY HONEST. Some statements appear similar but differ in important ways. Please take your time. As much as possible, please agree or disagree with each statement, and avoid making neutral responses unless you are totally unsure.

Please select the appropriate rating using the five-point scale.

1- Totally Disagree
2- Somewhat Disagree
3- Neutral
4- Somewhat Agree
5- Totally Agree

1. In an unfamiliar environment with no clear landmarks (e.g., forest, desert, new city) and/or in low visibility conditions (e.g., fog, heavy rain), I still have a good sense of where I am heading.

2. If I travel in a novel multi-level building, I can easily imagine the 3D structure of the space.

3. I tend to judge my orientation in the environment in terms of cardinal directions (north, south, east, west).

4. My mental representation of space reflects realistic, large-scale structural layout of my surrounding environment with relatively accurate distances.

5. If I need to return to my origin, it is easier for me to retrace my route than to find a new shortcut.

6. I usually attempt to visualize a map of the environment from a top-down aerial perspective as I travel.

7. It is easy for me to estimate the distance and direction between my moving body and the landmarks I have passed by on the route.

8. If I were to return to my origin, I would attempt to find a shortcut based on judging the direction-of-return to the origin rather than retracing my footsteps.

9. My mental representation of the route that I traversed is analogous to a schematic map (e.g., floor-plan, blue-print, metro map) rather than a first-person perspective of routes and landmarks.

Appendix D. Sample questions from the Survey of Autobiographical Memory (SAM) (Palombo et al., 2013).
The following questions relate to your memory. Please indicate the degree to which you agree with each statement.

1- Strongly Disagree
2- Disagree Somewhat
3- Neither Agree nor Disagree
4- Agree Somewhat
5- Strongly Agree

A. Event Memory:

The first questions concern your memory for past events from a specific time and place for which you were personally involved. Events are defined as occurring within a day or less. For example, a three-week vacation is not considered a specific event, but something that happened on one day during your vacation is considered a specific event.
The questions apply to events that happened at least 3-4 weeks ago (as opposed to something that happened just a few days ago). When answering, don't think about just one event; rather, think about your general ability to remember specific past events.

1. Specific events are difficult for me to recall.
2. When I remember events, I have a hard time determining the order of details in the event.
3. When I remember events, in general I can recall objects that were in the environment.
4. When I remember events, in general I can recall what I was wearing.
5. I am highly confident in my ability to remember past events.
6. When I remember events, I remember a lot of details.
7. When I remember events, in general I can recall which day of the week it was.
8. When I remember events, in general I can recall people, what they looked like, or what they were wearing.

C. Spatial Memory

These questions deal with your spatial memory (i.e., your ability to orient yourself in new or old environments).

1. In general, my ability to navigate is better than most of my family/friends.
2. After I have visited an area, it is easy for me to find my way around the second time I visit.

3. I have a hard time judging the distance (e.g., in metres or kilometres) between familiar landmarks.

4. I get lost easily, even in familiar areas.

5. If my route to work or school was blocked, I could easily find the next fastest way to get there.

6. I use specific landmarks for navigating.

Appendix E. www.WorldFitnessLevel.org questionnaire (Nes et al., 2011).

Step 1.

1. What is your country and city of residence?

2. What is your ethnicity?

3. What is your highest level of education?

Step 2.

4. What is your gender?

5. How old are you?

6. How tall are you?

7. How much do you weigh?

Step 3.

8. What is your maximum heart rate?

Step 4.

9. How often do you exercise?
    a. Almost never or less than once a week
    b. Once a week
    c. 2-3 times per week
    d. Almost every day
    e.
10. How long is your workout each time?
    a. Under 30 minutes
    b. 30 minutes or more
    c.
11. How hard do you train?
    a. I take it easy without breathing hard or sweating
    b. Little hard breathing and sweating
    c. I go all out

Step 6.

12. What does your waistline measure?

13. What is your resting pulse?

Appendix F. Borg Rating of Perceived Exertion Scale (Borg, 1982)

Rating	Perceived Exertion
6	No Exertion
7	Extremely Light
8	
9	Very Light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very Hard
18	
19	Extremely Hard
20	Maximal Exertion

Appendix G. Internal Validity - MAPE calculations for Polar Pacer Pro GPS watch

Watch Number	Researcher	Speed	Course Direction	Average Count Metre Distance (km)	Watch Distance (km)	APE
1	A	Walk	Forward	1.32	1.37	3.79
1	B	Walk	Forward	1.32	1.32	0.00
1	A	Run	Forward	1.32	1.29	2.27
1	B	Run	Forward	1.32	1.32	0.00
1	A	Walk	Reverse	1.32	1.35	2.27
1	B	Walk	Reverse	1.32	1.36	3.03
1	A	Run	Reverse	1.32	1.30	1.52
1	B	Run	Reverse	1.32	1.29	2.27
					MAPE	**1.89**
2	A	Walk	Forward	1.32	1.33	0.76
2	B	Walk	Forward	1.32	1.38	4.55
2	A	Run	Forward	1.32	1.33	0.76
2	B	Run	Forward	1.32	1.30	1.52
2	A	Walk	Reverse	1.32	1.33	0.76
2	B	Walk	Reverse	1.32	1.34	1.52
2	A	Run	Reverse	1.32	1.28	3.03
2	B	Run	Reverse	1.32	1.31	0.76
					MAPE	**1.70**

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