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PHYSICAL FATIGUE NEGATIVELY AFFECTS DECISION-MAKING DURING A CLOSING-GAP APERTURE CROSSING TASK WHEN USING JOYSTICK-CONTROLLED LOCOMOTION

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By

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THESIS ABSTRACT

Goal-direct locomotion is made possible through the integration of sensory input from the visual, vestibular, and somatosensory system. However, changes in collision avoidance behaviours and action capabilities (i.e., affordances) may occur when a sensory conflict is introduced (i.e., via incongruent input from a sensory system). Further, changes to the person (such as physical fatigue) may have negative implications on the cognitive abilities of an individual following physically fatiguing exercise. This in turn could affect an individual's ability to avoid collisions with objects or other individuals in their environment. Thus, the objective of this thesis was to explore how physical fatigue affects decision-making during a closing-gap aperture crossing task using joystick-controlled locomotion. The purpose of Study 1 was to determine if joystick-controlled locomotion is a viable tool to study young adult aperture crossing behaviours in virtual reality (VR). Using this tool would remove any potential physical effects from the task, which then allowed for the study of how physical fatigue specifically affects cognition (i.e., decision-making). Study 1 determined that passability decisions (i.e., 50% Switch Point) and response time (i.e., TTC) were significantly larger during the joystick-controlled locomotion interface compared to real-walking, yet still within an acceptable range to consider the task accurately completed. Thus, young adults are able to accurately complete the aperture crossing task whether physically moving or using a joystick to control locomotion. Study 1 also determined a critical point for crossing closing gaps in VR (joystick-controlled locomotion: 1.34x shoulder width; real-walking: 1.8x shoulder width), which informed the threshold by which accurate performance was determined. The purpose of Study 2 was to determine if physical fatigue affects cognition in recreationally active young adults, and whether those effects are reflected in behaviours when passing through a closing-gap aperture. Physically fatigued individuals exhibited no deleterious changes in passability decisions (i.e., 50% Switch Point), but increased response time (i.e., TTC) when following through on decisions. In conclusion, young adults behave similarly in VR regardless of locomotion interface, and physical fatigue induced by a fatiguing cycling protocol alters cognitive processing, which has implications for behaviour in collision avoidance situations.

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CHAPTER 1 – REVIEW OF THE LITERATURE

1.1 VISUAL CONTROL OF MOVEMENT

1.1.1. Visual Control of Locomotion

Avoiding obstacles and steering to a goal are visually-guided movements that occur on a daily basis (Lee, 2012). More importantly, perceiving an oncoming object and making the necessary avoidance behaviours is essential to safely move through one's environment without colliding with the object. Perception is the process of gathering information about the environment, the movement of the self through an environment, and of the body segments relative to themselves and the environment (Patla, 1998). Further, the visual system is one of the only sensory systems to provide feed-forward control of movement (i.e.,, sensory information acquired at a distance; Patla, 1998). As a result, the visual system plays an essential role in locomotion by providing visual information of the environment in advance, which allows for smooth locomotion through cluttered or uneven terrain (Patla, 1997). This proactive control of locomotion allows for effective steering through the environment, while avoiding collisions.

Actions in a cluttered environment such as steering to a goal are controlled by optic variables such as optic flow, yet optic flow is only available as one acts or moves within the environment (Gibson, 1979). Optic flow can be described as the changing pattern of light on a surface, which provides perceptual information about the rate and direction of movement of objects in the visual field (Lee & Kalmus, 1980) Using visual information to guide movement in this manner can also be described as perception-action coupling. The coupling of environmental perceptions and actions in the environment is essential in guiding goal-directed behaviour, such that visual perception is guided by action, and action in turn is guided by perception (Gibson, 1979).

Many researchers view perceptual information of the environment as a major determinant of action capabilities (e.g. Loomis & Beall, 1998). In other words, the information gathered from the environment gives an indication of how one might act in such an environment (i.e.,, terrain, obstacles, other moving people). However, this view is incomplete, as there are controlling factors that must be considered which contribute towards the control of locomotion. One such factor is the spatial envelope of an individual's own body. When navigating a cluttered environment, uneven terrain, or narrow pathway, one must take into account the body's own dimensions (Loomis & Beall, 1998). Using an example such as a narrow walkway, if one's body dimensions are too large to safely walk along that pathway, no amount of rich perceptual information will change that fact. Another factor to consider is that locomotion is constrained by the physical properties of the body, known as body dynamics. Body dynamics can be used to predict the outcome of a movement, which is essential in controlling locomotion safely. An actor must have knowledge of their action capabilities (i.e.,, magnitude in which velocity can be adjusted) and body characteristics (i.e.,, position, orientation, size) in advance to determine whether they could move with enough speed to cross a busy street safely (Loomis & Beall, 1998). The degree to which there is a fit between the properties of the actor and the properties of the environment will govern successful control of locomotion.

Past research has sought to determine how both changes to the person and/or changes to the environment can affect behaviours during goal-directed locomotion. Changes to the person can be temporary (such as a concussion; Baker & Cinelli, 2014), or permanent (such as aging; Uc, Rizzo, Anderson, Shi, & Dawson, 2006). Both types of changes have been assessed in the literature, and the results from these studies demonstrate how changes in the behaviour of a person during a collision avoidance task can indicate a change or impairment in cognition, and thus the ability to visually guide locomotion. University-aged athletes who have sustained a concussion show poor visuo-motor control and decision making during collision avoidance, resulting in more collisions (Baker & Cinelli, 2014). Furthermore, older adults with a cognitive impairment such as Alzheimer's disease demonstrate poorer performance on a collision avoidance task. When using a driving simulator, 98% of older adults with Alzheimer's disease showed unsafe outcomes. Unsafe outcomes were predicted by poor performance on tests of visual perception, attention, visuospatial abilities, and executive function (Uc et al., 2006). These impairments in collision avoidance ability suggest that changes to the person can result in a reduced ability to effectively interpret and use visual information during locomotion. These changes are particularly important in collision avoidance situations, where failing to avoid an obstacle can result in a collision and the potential for body injury.

Conversely, changes to the environment can also affect behaviours during collision avoidance tasks. When locomoting over uneven terrain such as during a stone-stepping task, young adults use vision to fixate each stone just prior to stepping (Hollands, Marple-Horvat, Henkes, & Rowan, 1995). This suggests that adapting movement techniques to ensure skilled stepping onto uneven terrain uses feed-forward visual control mechanisms, which proved to be a robust mechanism in young adults. Moreover, Hackney and colleages (2015) tasked participants with a postural threat of walking over narrow and elevated surface while passing through narrow apertures, and observed that speed was significantly reduced, and trunk sway was significantly increased. In this situation, it was thought that the visuo-motor system had to adapt to the change in eye height in order to successfully avoid a collision (Hackney et al., 2015). Changes to the environment such as uneven, elevated, or narrow terrain elicit changes in behaviour to ensure safe movement to their goal. This requires an individual to proactively control their movement using visual information from the terrain. Both changes to the person and changes to the environment must be considered when observing behaviour in collision avoidance situations, as they are important factors that have an effect on the visual control of locomotion.

1.1.2. Collision avoidance

When approaching an obstacle or tracking an approaching object, the determination of time-to-contact is represented by the optic variable tau (τ). Tau has been referred to as the inverse rate of dilation of an image of a moving object on the retina (Lee, 1976). That is to say, the rate of expansion of the image indicates the time remaining before the individual and the obstacle collide (Lee, 1976). Tau contributes to the control of movement by using an individual's perceptions of the properties (such as size, shape, rate of movement, etc.) of the obstacle, and of the individual themselves, to signal that a change in locomotive behaviour is required to avoid a collision (Lee, Georgopoulos, Clark, Craig, & Port, 2001). Collision avoidance tasks that require individuals to pass through an aperture necessitate the use of tau during the approach to the aperture. Tau is used to determine the time remaining before a collision may occur, which allows for the decision to make an avoidance behaviour, in the event that an aperture is too small to pass through successfully. This decision is based on the angle between one's locomotor trajectory and the obstacle. These behaviours may include a shoulder rotation to fit through the aperture, or a decision to go around the aperture entirely. Additionally, when avoiding a collision with an approaching object, the rate of approach of the object (i.e., the optical expansion threshold) governs the speed of the individual's avoidance behaviour (Cinelli & Patla, 2007). Individuals use the optical expansion threshold when moving through an environment to determine the moment at which a change in movement velocity or direction is needed, to avoid a collision (Cinelli & Patla, 2008). These perceptual skills have shown to be important in successful avoidance of oncoming obstacles or when approaching and avoiding stationary obstacles. In this situation, optic variables such as optic flow and tau are required to provide information of the time remaining before a person moving toward an aperture makes contact. Specific populations such as young drivers (i.e.,, >2 years driving experience; average age 19.1) and older adults (65+) show less than optimal visual perception, reflected in their ability to determine time-to-contact in a collision situation (Barbet, Meskali, Berthelon, Mottet, & Bootsma, 2006). However, in the fundamental research conducted to determine the use of tau and the optical expansion threshold, young adults have demonstrated the most effective use of visual information to control locomotion (Cinelli & Patla, 2007; Cinelli, Patla, & Allard, 2008; Patla, 1998).

1.1.3. Tau Coupling

Passage through an aperture while avoiding a collision requires individuals to use visual information about the environment to help determine where an aperture is located in space, and its properties (i.e.,, size, orientation, etc.). Additionally, individuals must use information regarding their own body size, rate of self-motion, and must have the ability to alter either. In situations in which an aperture is closing at a constant rate, similar to encounters with subway doors or elevator doors, the time it takes for the two sides of the aperture to meet is considered tau of a gap (Lee et al., 2001). When approaching such a closing gap or aperture, individuals must simultaneously control the spatial gap between themselves and the aperture (tau) in relation to the closing gap of the aperture (tau of a gap), known as tau-coupling (Lee et al., 2001). Tau coupling can be applied to many different goal-directed behaviours, such as passing through an aperture of constantly changing widths without colliding with either side (Cinelli et al., 2008). For example, Lee and colleagues (2001) tasked individuals with a goal of moving a mouse cursor to intercept a moving circle on a computer display, the successful strategy would be to match the decreasing tau of the mouse cursor to the decreasing tau of the moving circle. Correct tau coupling ensures that each gap closes at the same moment, and the mouse cursor and the moving circle intercept each other. Accurate behaviour when passing through a closing aperture requires the actor to have access to predictive visual information to control the closing gaps between themselves and the aperture, and the speed of closure of the gap itself (Lee, 2001). Therefore, vision accurately guides locomotion (steering) through an environment.

When steering toward a target that is changing position, the actor must use optical variables and employ an interception strategy, as outlined by Fajen and Warren (2004). This requires the actor to proceed at a target-heading angle (β), defined as the visual angle between the actors' current direction of travel ($\tau_{approach}$), and the moving position of the target ($\tau_{aperture}$), which is at a certain distance from the actor. Intercepting the target requires the actor to walk in a straight path ahead of the target, such that the β angle is held constant at each iteration in time during the approach (Fajen & Warren, 2007). In the case of passing through a closing aperture, keeping the β angle constant would result in the actor reaching the aperture at the moment that the aperture closed, and thus it would result in a collision ($\tau_{approach} = \tau_{aperture}$). However, if the goal is to pass through the aperture, then an avoidance strategy would be required instead of an interception strategy. A successful avoidance behaviour would be to approach at a constantly increasing β angle, such that the time of crossing occurs prior to the time the two doors meet. This can be likened to tau-coupling, such that when $\tau_{approach} > \tau_{aperture,}$ the result is successful aperture crossing. If the β angle were decreasing ($\tau_{approach} < \tau_{aperture}$), the aperture would be closed prior to the actors' arrival at the aperture. Tau-coupling is important in one's everyday movement when closing the gap between themselves and their goals, to arrive in the right place at the right time.

1.1.4. Affordances

Gibson (1979) argued that affordances are the activities that an object or situation offers, with certain action capabilities. For example, a cup affords grasping if its size, shape, and orientation are compatible with the size and grasping abilities of the hand. These affordances remain constant during a change in the observer (Goldstein, 1981). Affordances based on body-scaled information allow for actions to be based on the ratio between the environmental dimensions and the individuals' body dimensions (Warren & Whang, 1987). Individuals use an intrinsic measurement of the affordances of the environment, which results in a dimensionless, body-scaled ratio that assists in determining the required actions, and when a change in action is required (Warren & Whang, 1987). Other affordances may involve variables expressed in units that are considered action-scaled, such as velocity or acceleration. Behaviours are action-scaled when the action performed in the environment are limited to the abilities of the individual. Action-scaled information is essential in the visual control of locomotion, as it is used to determine the possible activities or courses of action in any situation (Warren, 1984). Time-to-contact information is one element that contributes to successful control of locomotion, and has a role in regulating locomotion when avoidance behaviours are required.

Obstacle avoidance research has determined that the point where the affordances of an aperture require a change in an individual's actions is called the *Critical Point* (Warren & Whang, 1987). The passability of the aperture may be based on the body-scaled ratio between an individual's shoulder width and the width of the aperture (Hackney, Vallis, & Cinelli, 2013). If an aperture is determined to be too narrow to pass through normally, a change in action is required, such as a shoulder rotation, to pass through avoiding a collision. This is an essential skill when navigating apertures and avoiding obstacles in everyday life. Factors affecting critical point can be affected by either changes to the person such as age or speed of movement, or changes to the environment such as obstacle properties. For example, Warren and Whang (1987) determined that when walking or running through static apertures of several difference widths, young adults chose to rotate their shoulders to fit through at a critical point of 1.3 times their own shoulder width. When given the same task of walking through a similar static aperture, older adults demonstrated a critical point of 1.6 times shoulder width (Hackney & Cinelli, 2011). Further, if actions are constrained by artificially altering body dimensions (such as holding an object or using a wheelchair), safe aperture passage is based on one's action capabilities (such as slowing down) (Higuchi, Cinelli, Greig, & Patla, 2006). Additionally, when human obstacles are used instead of pole obstacles, critical point was found to be 1.7 times shoulder width (Hackney et al., 2015). This may be due to the participant considering possible movement from the human obstacle, whereas this was not necessary for a pole obstacle, or other psychosocial factors. However, all of these studies measured aperture crossing behaviours with static obstacles and not moving obstacles.

1.2 VIRTUAL REALITY

1.2.1. Virtual Reality as a Tool

Virtual reality (VR) has been used in research to measure executive function, a broad term for cognitive processes such as cognitive flexibility, reasoning, decision making, and others (Diamond, 2013). Further, testing executive function using VR is correlated with traditional neuropsychological measures, which suggests VR is a useful tool for studying cognition and decision-making, through tasks such as the Stroop task or the trail-making task (Davison, Deeprose, & Terbeck, 2018). Street crossing behavior is an example of one task that has been studied in VR to assess decision-making abilities (Zito et al., 2015). For ethical reasons, studying collision avoidance situations in this manner is only possible through a virtual environment. The speed which the display is updated during movement, the wide field of view of the head-mounted display (HMD), and the use of a participants' natural movements creates a life-like sense of realism within the VR environment that provides a true sense of immersion (Tarr & Warren, 2002).

Previous uses of VR focusing on cognition and decision-making suggests that VR is an ecologically valid and useful tool in studying collision avoidance behaviours.

1.2.2. Virtual Navigation and Multisensory Integration

In recent years, VR has undergone major technological advancements, which have had a significant impact on users sensory experience and the many possible ways VR can be useful in research (Boletsis, 2017). Over the years, many locomotion techniques have been developed to facilitate user-friendly navigation in the virtual world. One technique is real-walking locomotion, a room scale-based navigation technique where the user interacts with the virtual world inside a limited physical space, and their position and orientation are determined by tracking the position of the HMD worn by the user (Boletsis, 2017). Real-walking locomotion has previously been viewed as cumbersome and unfeasible in the laboratory space. However, as the use of HMD virtual environments become more commonplace, real-walking locomotion, despite being limited to the laboratory environment size, is considered the best method of navigation in terms of presence, ease of use, and naturalness (Slater, Usoh, & Steed, 1995). Further, this locomotion interface allows for the user to maintain intact multisensory integration, as visual, somatosensory, and vestibular information is available to accurately inform locomotion behaviour (Cirio, Olivier, Marchal, & Pettré, 2013).

Another navigation technique used in VR is controller-based, where a controller is utilized to move artificially in the VR environment (Boletsis, 2017). The interaction space is open and unlimited, and is facilitated using joystick-based controls. Controller-based navigation is the second most commonly used locomotion technique in VR research, with walking-in-place being the most common (Boletsis, 2017). Artificial navigation allows for a less physically demanding experience, as the user stands stationary while using a controller to move (Boletsis, 2017). In controller-based navigation, walking is achieved by pushing the joystick forward, which causes forward movement. To terminate walking, the user simply releases the joystick. This method has high precision and accuracy, as well as a low latency (Nabiyouni, Saktheeswaran, Bowman, & Karanth, 2015). However, this type of virtual navigation interface does not preserve all sensory inputs involved in locomotion, as the individual is not receiving congruent somatosensory and vestibular information pertaining to the task.

Marsh and colleagues (2012) evaluated the cognitive implications of using different locomotion interfaces by asking individuals to remember sequences of either spatial or verbal items while completing a task using real-walking and joystick locomotion. Despite the differences in available sensory input between the two locomotion interfaces, when comparing a joystick interface (least natural) to a real-walking interface (most natural baseline), there were no differences between them. Research on the feasibility, ease of use, validity and reliability of VR suggest that both real-walking and joystick navigation are viable methods to study collision avoidance and aperture-crossing behaviours.

1.3 FATIGUE AND COGNITION

1.3.1. Embodied Cognition

Perception of the world occurs based on our abilities to act on it, therefore when our perceived abilities change, so too do our perceptions (Witt, Linkenauger, Bakdash, & Proffitt, 2008). For example, people perceive targets to be farther away when throwing heavy balls compared to light ones, and a batter who is hitting well perceives softballs to look larger than those not hitting well (Witt, Proffitt, & Epstein, 2004, 2005). In perception, visual input relative to the environment is scaled to the action-specific abilities of the perceiver (Witt et al., 2008). This is often referred to as embodied perception (Proffitt, 2006). In fact, hills appeared steeper to individuals who had completed fatiguing runs lasting between 45 and 75 minutes, and those wearing heavy backpacks (Bhalla & Proffitt, 1999). As such, fatigue may affect one's ability to act on the world in a habitual manner causing passable closing gaps to be perceived as impassable

1.3.2. Deficits in Cognition Following Fatiguing Exercise

Cognition is defined as the process of acquiring knowledge and understanding through thought, experiences, and the senses (Gailliot, 2011). Optimal cognitive functioning is essential throughout the lifespan as it is associated with other abilities such as school performance, better mental health, reduced susceptibility to mental illness, and others (Gailliot, 2011). One component of cognition is the central executive, which is a higher order neural process that allows for self-control and higher-order cognitive abilities such as decision-making and logical reasoning (Gailliot, 2011). The decision-making element of cognition is essential during successful locomotion and collision avoidance, as it is the link that connects perception of the world and an individual's response to it (Doya & Shadlen, 1992). Despite its importance, deficits in decision-making develop when the body is physically fatigued (i.e., after strenuous exercise), which can be problematic (Fleury & Bard, 1987). Physical fatigue is a change to the person that has been cited in the literature to cause changes in behaviour during locomotion (Carroll, Taylor, & Gandevia, 2016). Physical fatigue has been quantified using measures of neuromuscular fatigue, such as maximal voluntary contractions (MVC; Bentley et al., 2000). During vigorous intensity physical exercise, a sustained effort reduces the ability to produce voluntary force (Carroll et al., 2016). Further, in past fatiguing exercise protocols (e.g. 30min cycling @ 80% VO_2 followed by four 1min sprints @ 120% VO_2 with 1min rest in between; 30min cycling @ 80% VO_2 at preferred cadence and $\pm$ 20% preferred cadence), neuromuscular fatigue was demonstrated via a decline in MVC, which was associated with central and peripheral fatigue (Bentley et al., 2000; Lepers, Millet, & Maffiuletti, 1982). The reduction in the central nervous system's ability to maximally activate muscle is defined as central fatigue, where peripheral fatigue is associated with reductions in muscle action potential (transmission failure) and twitch characteristics (contractile failure) (e.g., Fitts, 1994; Rodriguez-Falces & Place, 2018; Sharples, Gould, Vandenberk, & Kalmar, 2016).

1.3.3. The Inverted U hypothesis

The relationship between cognitive performance and the arousal level of the central nervous system is well-known, and often illustrated by an inverted-U curve (Yerkes & Dodson, 1908). Also known as the Yerkes-Dodson law, performance on a cognitive task increases until an optimal arousal level, after which any further increase in arousal results in detrimental performance on the cognitive task (Hüttermann & Memmert, 2014). In the literature, the inverted-U curve is studied using physically fatiguing exercise as the arousal stimulus (McMorris, Delves, Sproule, Lauder, & Hale, 2005; Mcmorris et al., 2003). Often, cognitive performance is evaluated following physically fatiguing exercise, characterized by measures of neuromuscular fatigue (see section 1.3.2.). When performing a cognitive task following physically fatiguing exercise (eg. running or cycling), cognitive performance may fall below even resting values, resulting in an inverted "J" effect (as opposed to an inverted-U), and impaired performance on cognitive tasks (Terry McMorris, Hale, Corbett, Robertson, & Hodgson, 2015). More specifically, physically fatiguing exercise and the resulting neuromuscular fatigue causes deficits in cognition such as decision-making and processing of visual information (Féry, Ferry, Vom Hofe, & Rieu, 1997; Hancock & Mcnaughton, 1986). Fery and colleagues (1997) gave recreationally active participants a series of consonants to remember during a pedal to fatigue session, after which they were given a letter and asked to respond “yes” or “no” to whether that letter was present in the previous series. Following fatiguing exercise, more errors were made, and reaction time was slower. Further, participants with a VO_2 max of 38.33 ± 5.2 who pedaled on a cycle ergometer at 60% and 80% of peak power output demonstrated impaired performance (i.e., increased reaction time and incidence of errors) on a modified Stroop task, especially during the executive components of the task (i.e., switching condition; Labelle et al., 2014). However, some studies report null findings or even facilitating effects of fatiguing exercise on executive function. Active students (average $VO_2 = 47 \pm 9$ ml/Kg/min) showed no changes on a reaction time task following cycling exercise at a light (ventilatory threshold – 20%), moderate (ventilatory threshold), or very hard level (ventilatory threshold + 20% (Davranche, Brisswalter, & Radel, 2014). Additionally, recreationally active students (females: 35.4 ± 3 ml/Kg/min; males: 43.1 ± 4 ml/Kg/min) were found to exhibit improved speed of reaction time following 35 minutes of cycling at 90% of ventilatory threshold (Audiffren, Tomporowski, & Zagrodnik, 2008). Evidently, there are inconsistencies in the literature that likely contribute to the different findings surrounding cognitive performance following physically fatiguing exercise. Many reviews of the existing literature fail to consider population characteristics as a potential confounding variable (i.e., fitness level). Hüttermann and Memmert (2014) found that the inverted-J function applies to non-athletes, such that performance decreases after an optimal point. Conversely, trained athletes demonstrate linear improvements in performance, and do not reflect the inverted-J function on cognitive tasks. Thus, reviews that include all populations tend to conclude no effect of fatiguing exercise on executive function (Lambourne & Tomporowski, 2010). However, in studies where sufficient direct or indirect evidence of fatigue is provided and the test population is recreationally active or sedentary, the effects of fatiguing exercise on executive function are deleterious. Many different tasks have been utilized to evaluate decision-making after fatiguing exercise, however very little research exists that investigates decision-making performance during a collision avoidance task. It is important to study how collision avoidance behaviours differ among populations (i.e., physically fatigued), as it will assist in understanding executive function and how individual's action capabilities (i.e., affordances) are affected when the body is physically fatigued by a fatiguing cycling protocol.

1.3.4. Speculative Physiological Mechanisms

Past researchers have proposed mechanisms to explain the physiological changes that cause a change in cognitive performance following physically fatiguing exercise. The first and most plausible hypothesis to explain the findings of the current study, is that following the fatiguing exercise, glycogen stores in the brain were depleted, which in turn impaired executive functioning. The functioning of the central executive is in part determined by levels of brain glycogen, which is stored in small amounts in astrocytes, a glial cell primarily located in grey matter (Gailliot, 2011; Wender et al., 2000).

The central executive is metabolically expensive, and thus requires large quantities of glucose compared to other cognitive processes. Interestingly, one function of the central executive is persistence at physical exercise, as an individual maintains a constant drive to continue moving and resist giving up (Gailliot, 2011). This task of physical persistence thus also requires brain glycogen (Baumeister, Muraven, & Tice, 1998). In fact, behaviours requiring self-control (such as physical persistence) draw from the same pool of limited self-regulatory strength, which can be depleted by acts using self-regulation, and are not quickly replenished (Bray, Martin Ginis, Hicks, & Woodgate, 2008). Therefore, during periods of fatiguing exercise with high cortical energy and self-regulatory requirements, glycogen stores and self-regulatory strength may be depleted (i.e., hypoglycemia; Gailliot, 2011). At a neuronal level, low levels of glucose in the brain reduced the rate of synaptic transmission in pyramidal cells (Fan, O'Ragen, & Szerb, 1988). When synaptic transmission is attenuated, participants ability to process visual information and act on passability judgements may be delayed.

Another explanation is the hypofrontality hypothesis proposed by Dietrich (2003), which predicts a decline in complex mental processes during periods of physical activity. The brain has finite metabolic resources, and the process of initiation, control, and maintenance of motor movements requires a large amount of metabolic resources. Essentially, this hypothesis predicts deactivation in prefrontal cortex during strenuous exercise, and the brain reacts by modifying its resource allocation (Dietrich, 2003). Following the onset of physical fatigue, the processes of perception and action which involve the prefrontal cortex may be due to increased activation of motor and sensory systems (Dietrich & Audiffren, 2011). The original hypothesis does not expect visual perception to be affected during exercise, however significantly longer premotor time has been recorded during a button-press simple visual reaction time task while cycling at 75% peak VO_2, potentially indicating deactivation in the prefrontal cortex (Ando et al., 2012). While visual perception is a bottom up process (i.e., perceiving stimuli from the environment), it does not solely determine perception. Top down signals based on the task (i.e., goal-directed locomotion, signals are derived from the individual's intentions) can also guide attention and perception (Buschman & Miller, 2007), which are derived from higher cortical areas such as the prefrontal cortex. Deactivation in the prefrontal cortex may affect top-down control of visual perception, and may explain the increased response time reported in previous literature examining executive function following physically fatiguing exercise.

Other studies suggest that neuroendocrinological changes could be a possible cause of cognitive changes following acute physically fatiguing exercise. Exercise activates the sympathoadrenal system and the hypothalamic-pituitary-adrenal axis, resulting in elevated brain concentrations of dopamine, norepinephrine, adrenocorticotropin hormone (ACTH), and cortisol. These physiological changes may increase arousal level during fatiguing exercise, and may cause neural noise (McMorris & Hale, 2012). This noise may cause variability in cognition (i.e., executive function), which may attenuate visual perception, causing an increase in response time (i.e., TTC).

1.4 THESIS OBJECTIVE AND HYPOTHESES

The overall objective of this thesis is to determine if joystick-controlled locomotion is a viable and accurate locomotion interface to investigate whether physical fatigue affects behavior on a closing-gap aperture crossing task.

The purpose of Study one (chapter 2) was to determine if collision avoidance behaviours were affected during aperture crossing in VR when vision was accurate, but somatosensory and vestibular sensory input was incongruent. This study was completed to determine if joystick-controlled locomotion was a viable tool to use to study recreationally active young adults' behaviours during a closing-gap aperture crossing task. During locomotion, accurate sensory information is up-weighted, and inaccurate information is down-weighted. Further, individuals heavily rely on visual information during locomotion. Therefore, it was hypothesized that primarily visual information is enough to complete a closing-gap aperture crossing task, and thus collision avoidance behaviours would be similar when using real-walking locomotion and joystick-controlled locomotion.

The purpose of Study two (chapter 3) was to determine if collision avoidance behaviours during the closing-gap aperture crossing task using joystick-controlled locomotion reflect negative effects following physically fatiguing cycling exercise. It was hypothesized that individual's perceptions of aperture passability would be affected by physical fatigue. Cognitive embodiment literature would suggest that after participants were physically fatigued, perceptions of their own action capabilities would be reduced, reflected by more conservative aperture crossing behaviours as they avoided colliding with a closing aperture. Further, time-to-contact would be reduced (based on past findings of increased response time following physically fatiguing exercise), indicating an increase in the time required make a passability judgement, and carry out a response (i.e., passing through or stopping).

CHAPTER 2

SENSORY CONFLICT ALTERS PERCEIVED ACTION CAPABILITIES DURING CROSSING OF A CLOSING GAP IN VIRTUAL REALITY

Abstract

The somatosensory, vestibular, and visual systems contribute essential sensory information to achieve multisensory integration, which facilitates locomotion around obstacles in the environment. The joystick-controlled virtual reality (VR) locomotion interface was developed to enable infinite virtual movement, but does not preserve all sensory input like real-walking. Our purpose was to determine if collision avoidance was affected during an aperture crossing task when somatosensory and vestibular input were incongruent, and only vision was accurate. Participants included 36 young adults who completed a closing-gap aperture crossing task in VR using real-walking and joystick-controlled locomotion. Switch point between passable and impassable apertures was larger for joystick-controlled locomotion compared to real-walking, but time-to-contact (TTC) was lower for real-walking than joystick-controlled locomotion. Larger joystick-controlled locomotion switch point indicates participants perceived more aperture closing speeds as passable during joystick-controlled locomotion compared to real-walking. Increased joystick-controlled locomotion switch point may be attributed to sensory conflict, which caused underestimation of distance to the aperture. This perceptual change can be considered for young adults as a margin of error for future VR applications which incorporate dynamically changing gaps. TTC may be different because gait termination must occur in real walking, but not in joystick-controlled locomotion. Future VR studies would benefit from programming acceleration and deceleration into joystick-controlled locomotion interfaces.

2.1 Introduction

During everyday locomotion, visual information is used to safely avoid obstacles (i.e.,, doorways) to reach a goal. One essential component of visual input is optic flow, which provides perceptual information about the rate and direction of movement of a person with respect to the environment as well as the objects in the visual field (Gibson, 2009; Lee & Kalmus, 1980). When approaching a static object such as a doorway, optic flow allows individuals to directly perceive the time remaining before a collision will occur (i.e.,, time-to-contact). Time-to-contact (TTC) information aids the control of locomotion by using an individual's own perceptions of the properties of the doorway (size, shape, rate of movement, etc.), and of the individual themselves, to signal whether a change in locomotor behaviour is required to avoid a collision (Lee, 2012). In such situations, one must determine whether or not the gap created by the doorway is passable (i.e.,, its affordances). The possibilities for action that an object or situation offers are known as affordances, which could be based on the relationship between the dimensions of the observer and the dimensions of the object (Gibson, 1979). As a result, the dimensions of objects in the environment are specified based on body-scaled information (Fajen, 2013). For example, the ratio between aperture width and shoulder width determines the passability of the aperture (Warren & Whang, 1987). Body-scaled information has been demonstrated to be useful for variables such as size and distance, specified as a ratio of eyeheight. As such, object height is specified as a multiple of the portion of the object that appears below eyeheight (Warren & Whang, 1987). Standing eyeheight has a constant relationship with shoulder width, and therefore could determine the boundary between passable and impassable apertures. When the eyeheight of participants was raised without their knowledge, individuals perceptions of aperture passability reflected their apparent eyeheight (Warren & Whang, 1987). Therefore, because action capabilities are based on the ratio between object size and body size, the perceptuomotor system must continuously update knowledge of these dimensions to adapt to the ever-changing environment (Hackney, Cinelli, & Frank, 2014). This becomes more challenging with a changing ratio, such as when gaps are dynamically changing.

Past studies which investigated the visual control strategies that guide locomotion through dynamically changing gaps have used fixed-width, moving apertures (Cinelli, Patla, & Allard, 2008), oscillating doors (Montagne, Buekers, Camachon, De Rugy, & Laurent, 2003), and shrinking gaps (Fajen & Matthis, 2011). Cinelli and colleagues (2008) and Montagne and colleagues (2003) found that when crossing oscillating doors, participants preferred to cross the aperture during the opening cycle, while decreasing their velocity to ensure safe and successful crossing. These behaviours do not fully reflect how individuals adjust their own action capabilities in a changing environment, as participants adjusted their crossing to optimize safety regardless of body size or locomotor capabilities. Thus, closing gap apertures allow for assessments of passability in a way that accounts for individuals' body size and locomotor capabilities. When perceiving the passability of closing gaps, participants use visual information (i.e., optic flow), which is supported by non-visual information (i.e., somatosensory and vestibular). In fact, when visual gain (i.e., the speed at which subjects move through the environment) was manipulated such that participants experienced faster than normal self-motion, non-visual sensory information allowed for re-calibration of self-motion information to maintain accuracy of predictions based on a new rate of self-motion (Fajen & Matthis, 2011). These results suggest that there are visual and non-visual contributions to perceptions of passability of closing gaps, and that manipulating sensory input can affect these perceptions.

The postural control system integrates visual and non-visual sensory information (i.e., somatosensory and vestibular) to ensure safe movement through the environment (Chien, Eikema, Mukherjee, & Stergiou, 2014). When perturbed, the postural control system is robust in its ability to recover from sudden loss of orientation information one or two systems (Assländer & Peterka, 2016). Further, the contributions of each individual sensory system changes when available sensory information changes, and the recalibrations of these sensory contributions is referred to as sensory reweighting (Assländer & Peterka, 2016; Karn & Cinelli, 2018). Reweighting of sensory input is common in everyday life when closing one's eyes, or when travelling over a compliant surface (Assländer & Peterka, 2016). Interestingly, when considering the unique contributions of each sensory system during locomotion, visual input is significantly upweighted during locomotion (Chien et al., 2014). This increased contribution of visual input reflects the importance of vision in the control of locomotion, and by extension, collision avoidance.

The objective of many past studies has been to perturb each sensory system to induce sensory reweighting, and determine how variables such as postural sway and sway variability are affected during locomotion. However, there remains an opportunity for further study of the functioning of the visual system when multisensory integration is perturbed or prevented, such as when perceiving passability of a closing aperture. Virtual reality (VR) platforms allow researchers to study the role of the visual system in performing a task when one or more sensory system is removed, essentially preventing multisensory integration. In virtual environments researchers are able to manipulate: the scene parameters; the interactivity of the individual within the environment; and/or the presented stimuli (van Veen, Distler, Braun, & Bülthoff, 1998). In recent years, different locomotion techniques have been developed for VR systems to facilitate user-friendly navigation, which has subsequently expanded its usefulness for scientific research (Boletsis, 2017). One locomotion interface is real-walking locomotion, where the user interacts with the virtual environment inside a limited physical space while wearing the head-mounted display (HMD), which simulates the virtual environment. Using real-walking in VR preserves congruent and complete sensory information (Cirio et al., 2013), which is advantageous, as it allows complete multisensory integration while performing tasks in the virtual environment. In VR environments where small physical space limits use, other interfaces have been developed which do not preserve all sensory input involved in locomotion and aperture crossing, but make up for the limited space available in VR designs. Such locomotion interfaces use a handheld joystick to simulate movement, which introduces incongruent sensory input from the vestibular system and somatosensory system (as the participant stands stationary in the laboratory environment, but visually perceives movement), but gain greater movement within the virtual environment (Slater et al., 1995).

As virtual locomotion relies predominantly on visual feedback, the elements of vision and perception of the virtual environment (i.e., field of view, optic flow) largely dictate behaviour outcomes (Cirio et al., 2013). The knowledge that visual information is heavily prioritized during virtual locomotion led to the purpose of this study, which was to evaluate young adults' behaviours on a closing gap aperture crossing task, when using primarily visual information (i.e.,, joystick locomotion) compared to when all sensory systems were available (i.e.,, real-walking), which preserves optimal multisensory integration. We hypothesized that participants would be able to accurately complete the task with the available visual information regardless of locomotion interface, reflected by similar passability decisions and time required to make decisions when real-walking and when using joystick-controlled locomotion.

2.2 Materials and Methods

2.2.1 Participants

36 healthy young adults ($\bar{x}$ 23.2 ± 1.8 years; 21 women, 15 men) were recruited to participate (see participant characteristics in Appendix G). Participants were included if they had normal or corrected-to-normal vision and were free from any injuries that would prevent them from physically walking through the simulated environment, and/or controlling their movement using a joystick. This study was approved by the Wilfrid Laurier University Research Ethics Board (REB #5764).

2.2.2. Protocol

Written informed consent was obtained from all participants prior to start of the study in compliance with the university's Research Ethics Board. Participants were outfitted with an HTC Vive™ HMD in order to provide an immersive VR environment experience. Once the HMD was placed on the participants' heads, they were allowed to walk around and free explore the VR environment to allow them to become comfortable and familiar with the simulated environment. Following the familiarization period and prior to the start of the experimental trials, participants completed 5 unobstructed steady-state walking trials of 7m with no changes to the VR environment. The steady-state walking trials were needed to establish each participant's normal walking speed. Next, the participants completed 84 experimental trials: two blocks of 21 randomized walking trials and two blocks of 21 randomized trials using joystick to simulate locomotion through the VR environment. The four trial blocks alternated between locomotion type (real-walking or joystick-controlled) and starting locomotion type was counter-balanced between participants. This block organization washed out any potential trial effect by strategically break up trials of each locomotion interface, and avoided oversaturation of either locomotion type. Participants were instructed to maintain their normal steady-state walking speed throughout all the walking trials and to avoid altering this speed for any reason. Additionally, each participant's normal steady-state walking speed was set as the constant movement speed during the joystick walking condition. Participants were given breaks when needed. Position data of the participants' head in space was recorded throughout the trial by the HTC Vive™ HMD at 90 Hz in order to determine the participants' behaviours.

2.2.3. Experimental Design

An aperture crossing task was selected for the experimental trials. The VR environment simulating the aperture crossing task was designed using Unity software. The VR environment represented the interior of an industrial building with set of large factory doors (4 m aperture width, 4.3 m tall; Figure 1) located 5m from the participants' starting location and a goal (i.e.,, square on ground) located 1 m beyond the doors.

Participants were instructed to walk (at their comfortable steady-state speed) towards the goal and not get hit by the doors. During the approach, the doors would begin to close as soon as the participants travelled 1 m (i.e.,, 4 m from doors) regardless of locomotion type. The closing rate of the doors on any trial was set at one of seven different speeds, determined by a multiplication factor based on each participant's steady-state walking speed (i.e.,, closing rate= walking speed * 1.2, 1.1, 1.0, 0.9, 0.8, 0.7, or 0.6). For example, if a participant approached goal at 1 m/s and the closing rate of the doors was 1.2*walking-speed, the doors would close at 1.2m/s and therefore be closed prior to the time when the participant would reach them. The closing rates of the doors were chosen ensured that at least one condition would be impossible to pass through (i.e., 1.2*), and one should be passable 100% of the time (i.e.,, 0.6*). If participants decided the doors were passable, they were instructed to pass through the aperture created by the doors and continue to the goal. If they decided the doors were impassable, they were instructed to stop their approach as soon as the decision was made. Participants completed the task using real-walking, where they physically moved through the VR environment, and also using joystick locomotion, where they would press a trigger on a handheld joystick to initiate movement, and would terminate movement by releasing the trigger. Participants were instructed to maintain their comfortable and consistent walking speed throughout each trial and avoid speeding up or slowing down as much as possible.

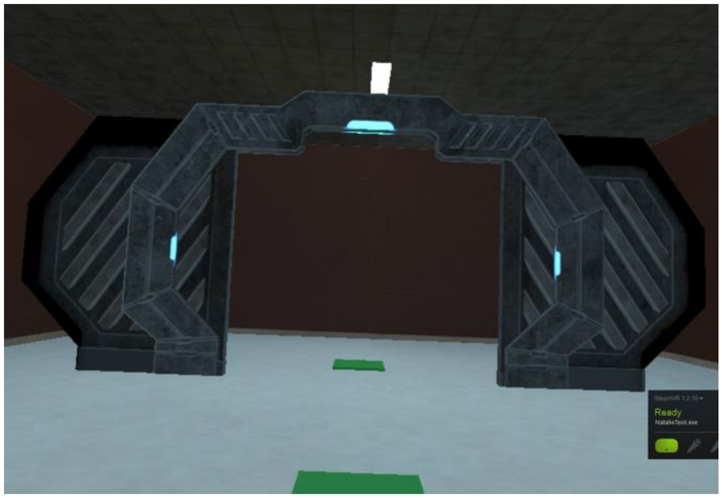

Figure 1. Simulated VR environment showing an open aperture. Participants would begin standing on the home square, and pass through the doors to reach the goal square.

2.2.4. Data and Statistical Analysis

Data were first sorted according to aperture condition (0.6*-1.2*walking-speed) within each locomotion interface (i.e.,, real-walking and joystick-controlled locomotion). For each interface, the proportion of trials (out of 6 per condition) in which each participant passed through the doors (0) or stopped (1) was recorded. Participant location at a change in speed (i.e., a stop) as well as which decision was made (pass through or stop) was determined by the HMD head position. Participant location when a stop occurred was recorded by the HMD as the distance between the participant and the aperture, or recorded as a 0 if the participant passed through. No feedback regarding aperture passage success was communicated to the participant. Within each interface, the proportion of trials in which a stop occurred within each of the 7 conditions (i.e.,, door closing speeds) was plotted, and a third order polynomial was generated. This was to determine the 50% switch point where a change in behaviour occurred (by solving for x where y=0.5), or the aperture condition where participants decided to pass through and stop an equal amount of times.

The average time to contact (TTC), or the time remaining before the participant would have reached the doors, was determined for the 1.0x, 1.1x, and 1.2x closing rates because participants stopped their approach during all trials, which allowed for analysis of TTC. This analysis was not possible for aperture conditions where a stop occurred less than 100% of the time (i.e., intermediate aperture closing speeds such as 0.8/0.9*walking-speed), as a pass through was recorded as a 0 for head position. TTC (s) was calculated using each participants' head position relative to the doors when they completed a stop (m) divided by their steady-state walking speed (m/s). For each participant, a 50% switch point and TTC values for each of the three aperture conditions were calculated for real-walking and joystick-controlled locomotion. Joystick and real-walking were compared using a Wilcoxon signed-rank test to determine any overall differences in the 50% switch point, and related-samples t-tests were conducted to determine differences in TTC values for conditions 1.0x, 1.1x, and 1.2x. Further, a one-way ANOVA was used to compare TTC within each locomotion interface across the 3 aperture conditions chosen. Last, One-way repeated measures ANOVAs were then run for each of the four variables (50% switch point, TTC values) comparing blocks 1 through 4 to determine if there was a block order effect on behavior. Results were reported as mean $\pm$ standard deviation; *p* values < .05 were accepted as significant.

2.3. Results

The Wilcoxon signed-rank test revealed a significant difference in 50% Switch Point overall between walking and joystick (p<.001, $t_{(34)}$=4.3), such that the 50% Switch Point for walking ($\bar{x} = 0.80 \pm 0.08$) was significantly lower than for joystick ($\bar{x} = 0.86 \pm 0.06$; Figure 2).

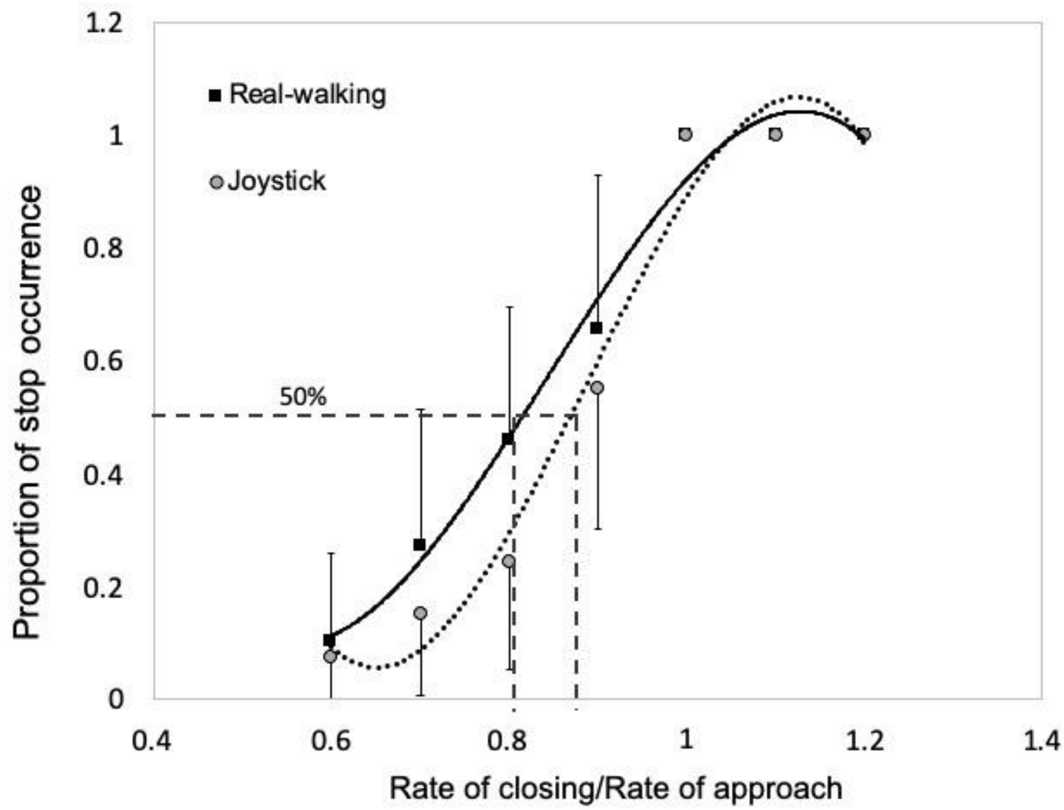

Figure 2. Average proportion of trials (± SD) for Joystick-controlled locomotion and real-walking where participants stopped prior to passing through the closing aperture for each aperture condition (rate of closing/rate of approach) with a 3rd order polynomial; average 50% Switch Point for each locomotion interface identified.

TTC averages for 1.0x, 1.1x, and 1.2x walking speed conditions were analyzed to compare the temporal characteristics of participants' behaviour during the task (Figure

3). Overall, in the 1.0x condition, TTC during real-walking was significantly less ($\bar{x}$ = 1.08 $\pm$ 0.32 s; *p*<.001, $t_{(35)}$=6.64) than joystick ($\bar{x}$ = 1.35 $\pm$ 0.36 s). Further, consistent with the 1.0x TTC results, there was a significant effect of locomotion type on TTC in the 1.1x condition (*p*=.002, $t_{(35)}$ =3.4), such that the TTC for walking was less ($\bar{x}$ = 1.14 $\pm$ 0.29 s) than joystick ($\bar{x}$ = 1.30 $\pm$ 0.32 s). Finally, in the 1.2x condition there was a significant main effect of locomotion type (*p*=.003, $t_{(35)}$ =3.23), such that the TTC for walking was less ($\bar{x}$ = 1.22 $\pm$ 0.37 s) than joystick ($\bar{x}$ = 1.40 $\pm$ 0.31 s). Despite this consistent difference in TCC between locomotion types, there was no difference within locomotion types (Joystick: *p*=.43; Walking: *p*=.21) across the three aperture conditions chosen. Finally, the one-way repeated measures ANOVAs revealed that block order (1 through 4, regardless of locomotion interface) did not have an effect on 50% Switch Point (*p* = .79, $F_{(1.9,31)}$=0.23), nor for TTC during the 1.0*walking-speed condition (*p* = .32, $F_{(3,32)}$=1.17), the 1.1*walking-speed condition (p = .32, $F_{(2.29,32)}$=1.16), or the 1.2*walking-speed condition (*p* = .09, $F_{(2.4, 32)}$ =2.4), suggesting repeated exposures did not impact the data.

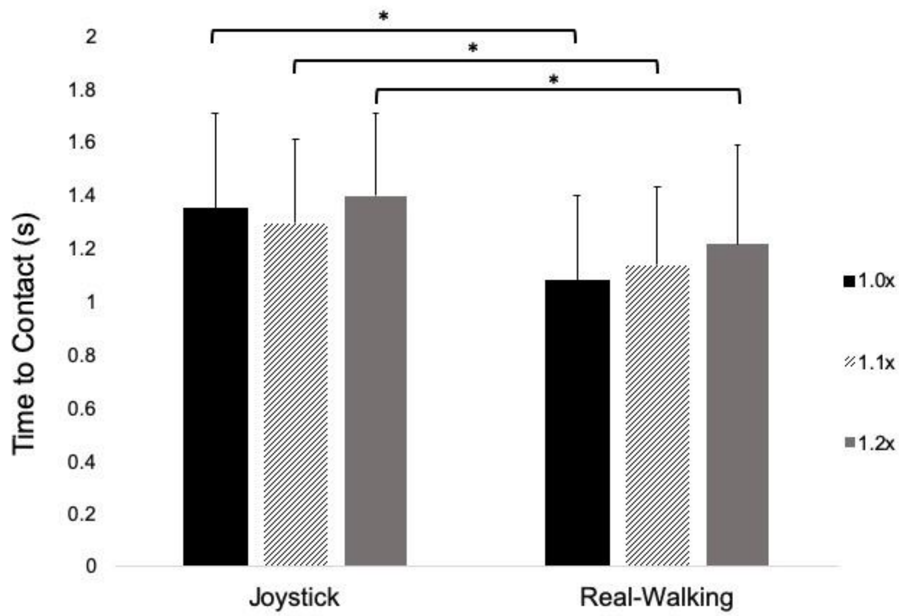

Figure 3. Mean time to Contact (TTC) and standard deviation bars for 1.0x, 1.1x, and 1.2x walking speed conditions. * indicates significant difference at *p*<.05.

2.4 Discussion

The objective of this study was to determine whether aperture crossing behaviour is consistent between two different locomotion methods: real-walking and joystick-controlled. Participants had a walking speed in VR ranging from 1.10 to 1.75 m/s ($\bar{x}$ = 1.4±0.23 m/s), equal to previously recorded average human walking speeds during walking in a real environment (Montufar, Arango, Porter, & Nakagawa, 2008). Real-walking locomotion requires integrated perceptual information from the somatosensory, visual, and vestibular systems, whereas joystick-controlled locomotion limits the individual to visual perceptual information. During the task, participants made a decision regarding passability while approaching a closing aperture at a constant speed, and followed through with their decision (whether a pass through or a stop). This required participants to make decisions based on their own capabilities, and not only the features of the objects in the virtual environment. The task was designed to determine if it was possible to complete a closing gap aperture crossing task accurately using visual information in absence of congruent vestibular and somatosensory information, or whether these sensory inputs were needed for triangulation of visual information. Since vision has a significant role during VR locomotion, it was hypothesized that the 50% Switch Point and Time to Contact would be similar between real-walking and joystick-controlled locomotion. Contrary to the hypothesis, a number of significant differences were observed, suggesting that visual perceptual information governing behaviour while crossing a closing aperture using Joystick-controlled locomotion is affected by incongruent somatosensory and vestibular information.

50% Switch Point

Previous foundational VR research has concluded that real-walking while wearing an HMD is the preferred locomotion interface in terms of presence, ease of use, and naturalness (Boletsis, 2017). Further, physically interacting with the virtual environment triggers the most intuitive user responses (Boletsis, 2017), and therefore the 50% Switch Point of 0.8*walking-speed (Figure 2) as determined in the present study likely reflects an individual's most natural response. Conversely, a 50% switch point of 0.85*walking-speed (Figure 2) as observed in the joystick-controlled locomotion, would indicate that individuals pass through apertures (gaps) closing slightly faster than real-walking. However, it is unlikely that the lack of congruent somatosensory and vestibular information fully explains the differences found in this study. One study that presented a novel Locomotor Sensory Organization Test discovered that when somatosensory and/or vestibular input is manipulated during locomotion, the presence of accurate vision greatly reduces the potential for gait instability (Chien et al., 2014). Therefore, the behavioural differences observed in the current study may arise from changes to how visual information is utilized when there is sensory conflict, rather than a direct effect of incongruent somatosensory and vestibular perceptual inputs. Considering the role of vision on performance during this task, information about body and self-motion from the visual system is given higher priority over information from other sensory systems during locomotion (Chien et al., 2014; Patla, 1997). Further, when somatosensory or vestibular sensory inputs are inaccurate, the nervous system will re-weight that information and upweight visual input to maintain balance, (Woollacott, Shumway-Cook, & Nashner, 2005), a conclusion that has also been observed in virtual environments (Lubetzky, Harel, Darmanin, & Perlin, 2016). During the present study, the upweighting of visual information may be problematic. When estimating travelled distance in a virtual environment using accurate sensory input from all senses, individuals provide accurate estimations, but underestimate distance travelled when making decisions purely based on visual information (Campos, Butler, & Bülthoff, 2014). It is possible that when using joystick-controlled locomotion, the individuals in the current study underestimated the distance between themselves and the doors, which resulted in perceived successful passage through faster door closing rates than during real-walking. As a result, the absence of complementary proprioceptive and vestibular input creates sensory conflict, and the up-weighted visual system is unable to perform adequately without the other two sensory inputs.

It is advantageous to compare these results to real life examples, however the majority of past research studying behaviour during aperture crossing used a critical point to determine performance. Critical point is defined as the point where the properties of the obstacle cause an individual to change their actions (Warren & Whang, 1987). Critical point divides performance into possible and impossible, however it does not necessarily portray what people can do consistently. Modelling affordances as a probabilistic function (i.e., 50% Switch Point generated from a polynomial) addresses the variable nature of performance. Instead of dividing performance into success and failure, a continuous function represents the probability of success at each unit of the environment (Franchak & Adolph, 2014). The 50% Switch Points calculated in the present study represent a threshold where behaviour changes, and the proportion of door passage is plotted at each door closure condition (Figure 2). A simple way to determine similarity in aperture crossing behaviour between VR and real life is to compare a 50% switch point to the equivalent critical point. For example, critical point, or door width compared to shoulder width for a 50% switch point of 0.8x (i.e., as found for real-walking), is equal to the aperture width at time of crossing divided by average shoulder width. The 50% switch point of 0.8x walking speed to critical point (CP) is given by:

$$CP = \frac{(W_{door} - (V_{door} \times T_{door}))}{\overline{SW}}$$

Where T_{door} is the time (sec) in which the participant reaches the threshold of the doors, determined by dividing the 4m approach distance with the average walking speed of the participants (1.4m/s). V_{door} is the rate at which the gap of the doors closed, determined by multiplying average walking speed (1.4m/s) by the 50% Switch Point (0.8* or 0.85*approach speed). W_{door} is the starting width of the door aperture (4m). Finally, average shoulder width ($\overline{SW}$) in this study was calculated to be 44.7cm. The resulting CP for real-walking was 1.8x shoulder width (i.e., 80cm aperture), and the CP for joystick-controlled locomotion was 1.34x shoulder width (i.e., 60cm aperture).

Most research concerning crossing of stationary apertures in real laboratory spaces find the critical point of young adults to be 1.4x shoulder width (Hackney & Cinelli, 2011; Warren & Whang, 1987; Wilmut & Barnett, 2010). However, when considering moving obstacles, it is difficult to identify past work that is comparable. Some researchers observed aperture crossing behaviours in response to oscillating doors, but looked at other behavioural measures (Montagne et al., 2003), or found that individuals almost always chose to pass through when the oscillating aperture was opening, not closing (Cinelli & Patla, 2008). Others have determined aperture crossing behaviours with two objects converging on a 45° angle toward the participant, unlike the current study (Watson et al., 2011). Thus, the current paradigm presents a new metric to understand aperture crossing behaviour in VR, particularly for crossing closing gaps. Further, this knowledge is specific to which sensory systems are contributing to performance on the task, whether all sensory input is available (i.e., real-walking), or when only visual input is available (i.e., joystick-controlled). Based on the calculated critical point of 1.8x SW during real-walking locomotion, when crossing a closing aperture in VR, individuals will pass through apertures that are at least 80cm wide on average. Comparatively, when using joystick-controlled locomotion (1.34x SW), individuals will pass through apertures at least 60cm wide, meaning they cross closing apertures with less medial-lateral clearance between the doors (i.e., distance between themselves and either door). Accordingly, we recommend that future VR paradigms which aim to study aperture crossing behaviour can effectively use a joystick-controlled locomotion interface, and acknowledge the differences in crossing behaviour as a margin of error when analyzing results. The ability to use joystick-controlled locomotion to study behaviour is favorable, as it enables researchers to study the visual control of locomotion and how collision avoidance is affected in populations where physically completing the task may be impossible or may introduce confounding variables. Examples of such confounders could be gait speed and variability in those with neurological impairment (i.e., multiple sclerosis) (Morris, Cantwell, Vowels, & Dodd, 2002), or spatial-temporal and kinetic parameters of gait following muscle fatigue (Barbieri, dos Santos, Vitório, van Dieën, & Gobbi, 2013).

Time to Contact (TTC)

The second variable analyzed was TTC values. On trials where a stop occurred, the TTC value represents how much time remained during the participants' approach before they would have collided with the doors. Inversely, it is a measure of how much time was required to make a decision of passability based on visual information of the closing gap, and to stop the approach (where a smaller value indicates longer decision-making time). Of the three conditions chosen for this analysis (1.0x, 1.1x, 1.2x), the 1.0x condition was considered the most challenging, as it was the slowest-moving aperture condition that was still impassable. A significant difference in TTC between locomotion types was determined in all three aperture conditions chosen for this analysis, where participants consistently stopped closer to the aperture while using the real-walking interface compared to when using joystick-controlled locomotion. This reduction in TTC can be attributed to an inherent mechanical difference present in the locomotion types (Brogan & Johnson, 2003). During joystick-controlled locomotion, a decision to stop was acted on by releasing the joystick trigger, and a stop occurred immediately. In the walking condition, once a decision to stop was made, gait termination was required, which takes time to produce. This action may explain the small but significant decrease in TTC in the real-walking condition compared to the joystick-controlled condition, as participants took one or more steps to terminate gait once the stop decision was made. In order to control for this difference, acceleration and deceleration functions should be built into future joystick-controlled paradigms to better simulate natural human locomotion and braking (Brogan & Johnson, 2003).

We considered TTC within each locomotion interface across the three conditions to determine whether the speed of door closure influenced TTC. No differences were observed between 1.0x, 1.1x, or 1.2x walking speed, which suggests that velocity of door closure does not have a relationship with stopping distance, only whether a stop is required or not. This conclusion is similar to Cinelli and Patla (2007), who found that during avoidance of an oncoming object, time of deviation from a straight path of the object was the same regardless of approach velocity, only velocity of avoidance was altered.

Conclusion

In conclusion, passability decision-making during a closing gap aperture crossing task in virtual reality is affected by locomotion interface. When vision is the only accurate sensory system available, the other incongruent senses create sensory conflict, causing aperture crossing behaviour to be less natural compared to when all senses contribute properly. Considering this difference as a margin of error allows future research to use joystick-controlled locomotion to study aperture crossing in absence of physical movement. For example, joystick-controlled locomotion would allow for the study of collision avoidance behaviours in those with neurological impairment (i.e., multiple sclerosis) (Morris et al., 2002), muscle fatigue (Barbieri et al., 2013), where physical movement may introduce confounding variables. Further, mechanical differences between the two locomotion interfaces may account for differences in TTC. Future research studying behaviour using Joystick-controlled locomotion interfaces would benefit from incorporating an acceleration and deceleration function into the locomotion interface to mimic natural gait initiation and termination more effectively. These results produce foundational knowledge regarding how VR platforms can be used to improve our understanding of human perception and behaviour, and the considerations that must be made when choosing a locomotion interface to study collision avoidance behaviour.

JUSTIFICATION FOR STUDY 2

The purpose of study 1 was to determine if joystick-controlled locomotion produced the same closing-gap aperture crossing behaviours as real-walking (considered the most natural virtual reality locomotion interface). If real-walking was used for study 2, it is possible that physically walking following a physically fatiguing cycling exercise would introduce confounding factors (i.e., decreased physical effort, inconsistent walking speeds) that could not be controlled for. Therefore, understanding how behavior may be affected by locomotion interfaced allowed improved comparability of study 2 results to a more natural scenario (i.e., real-walking in VR) when using only joystick-controlled locomotion.

The results of study 1 indicate that while 50% switch point and TTC variables were significantly different between the locomotion interfaces, they were within an acceptable range to conclude that the task was completed accurately using both locomotion interfaces. When considering a threshold from which to determine if joystick-controlled locomotion was a viable tool to use, critical point calculations were used. Using the calculation provided in study 1 (and assuming the same shoulder width and walking speed averages), the critical point associated with *0.9*walking-speed* is 0.9x-shoulder-width, or a 40cm aperture. The participants in this study had an average shoulder width of 44.7cm, and therefore, on average, a 0.9*walking-speed represents a threshold for achievable 50% switch points, above which was not acceptable, below which was acceptable. Thus, the switch points of *0.8*walking-speed* (real-walking) and *0.85*walking-speed* (joystick-controlled locomotion) are within acceptable values. In conclusion, the joystick-controlled locomotion interface could be used for Study 2, and would provide an accurate representation of what participant’s behaviour would be if they used real-walking locomotion.

CHAPTER 3

APERTURE CROSSING IN VIRTUAL REALITY: PHYSICAL FATIGUE AFFECTS DECISION MAKING

Abstract

Visual perception and cognitive (i.e.,, decision-making) abilities facilitate successful avoidance of obstacles. However, detrimental changes to cognition can occur after physical fatigue is induced by strenuous exercise. The purpose of the current study was to determine if obstacle avoidance behaviours reflect similar negative effects following physically fatiguing exercise. A virtual reality (VR) closing-gap aperture crossing task was completed by 13 recreationally active individuals to assess the effects of physical fatigue on decision-making ability (i.e., 50% Switch Point) and response time (i.e., time-to-contact; TTC). Participants approached closing apertures that moved at one of seven speeds (0.6, 0.7, 0.8, 0.9, 1.0, 1.1, or 1.2*walking-speed) while deciding to either pass through the closing aperture, or stop. Participants completed four blocks of trials (i.e.,, pre- and post-test) over two days (i.e.,, fatiguing constant-load cycling exercise day and a control day). No significant differences for 50% Switch Point were found across each of the blocks, but there was a significant reduction in TTC on the post-test exercise day. Thus, the type of decisions made during obstacle avoidance were not affected by physical fatigue, however the time required to make decisions (and follow through on the decision) was significantly increased. The current findings suggest that processes requiring more cortical areas and processing (i.e., response time) are more detrimentally affected by physically fatiguing cycling exercise compared to dichotomous visuomotor tasks (i.e., passability judgements).

3.1. Introduction

In everyday activity, crossing dynamically changing openings created by moving vehicles, other people, or doorways is relatively common, and individuals often navigate these obstacles successfully (Fajen & Matthis, 2011). To successfully cross a closing gap, one must gather the necessary sensory information in the environment, and guide their actions based on the available sensory input. In this scenario, visual information is essential for safe and successful passage.

Optic flow provides perceptual information about the rate and direction of the movement of objects in the visual field, as well as one's own movement through the environment (Gibson, 1979; 2009; Lee & Kalmus, 1980). Further, tau is an intrinsic optic variable which provides information regarding time-to-contact (TTC), or the time remaining before a collision with the obstacle (i.e., the doors) will occur (Lee, Georgopoulos, Clark, Craig, & Port, 2001). When crossing stationary obstacles, optic flow and tau information is sufficient to ensure safe crossing. However, in the case of a closing-gap aperture, one must take into account the time remaining before reaching the aperture (i.e., Tau of approach), but also consider the time remaining before the aperture itself closes (i.e., Tau of doors). Coupling ones approach with the closing of the doors is known as tau-coupling, which is required to ensure one passes safely through the closing gap (Lee et al., 2001). Past literature on closing gaps has found that individuals are easily able to complete this task, even when experiencing visual perturbations such as alterations to visual gain (Fajen & Matthis, 2011).

When assessing the passability of a closing aperture, selecting the appropriate action requires the perception of one's own movement capabilities, known as action-scaled affordances (Fajen & Matthis, 2011). The possibilities for action that an object or environment offers are referred to as affordances, which are based on the relationship between the properties of the observer and the properties of the object (Gibson, 1979). Therefore, the action strategies that individuals use to pass through a closing gap are dependent on properties of the individual (body size, walking speed, etc.) relative to the physical properties of the closing gap (i.e., size, shape, rate of movement), which together determine the affordances available to the individual (Gibson, 1979). When coupling door closure rate to one's preferred walking speed, individuals, on average, tend to perceive apertures closing at 0.8*walking-speed (i.e., 80% of preferred walking speed) or slower as passable, and aperture closing speeds higher than 0.8*preferred walking speed as impassable (as determined in Study 1). The 0.8*preferred walking speed is considered an individual's 50% Switch Point; a variable used in closing gap aperture crossing tasks to determine where an individual's action capabilities (i.e., affordances) switch from possible to impossible (Franchak & Adolph, 2014).

Acting on these passability judgements indicates that a choice was made based on the perceptual qualities of the environment (Doya & Shadlen, 1992). Therefore, it is important to consider that there is a cognitive decision-making component (i.e.,, central executive; Doya & Shadlen, 1992) which connects perception to actions (Figure 1). During goal-directed tasks such as crossing a closing aperture, optimal executive function is essential for successful completion of the task.

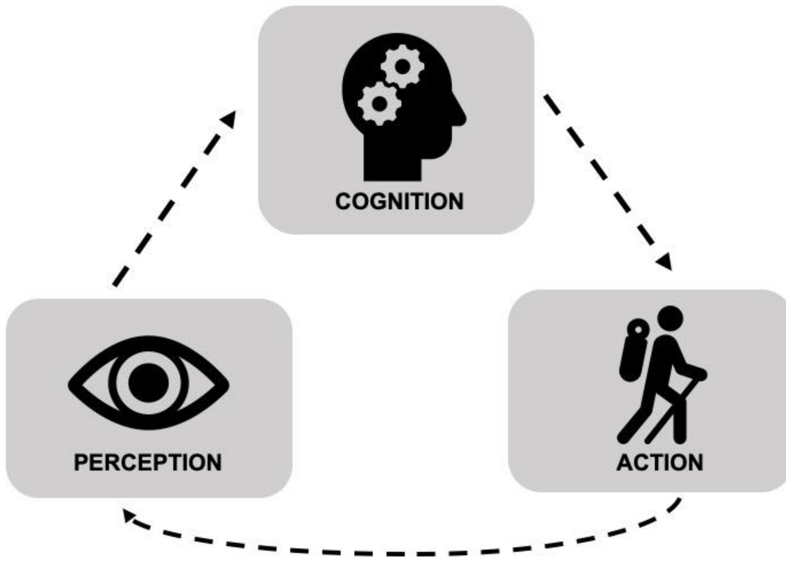

Figure 1: Simple model of perception-action cycle cognition as the link between perception and action (and where decision-making occurs)

The central executive can be negatively affected by changes to cognitive status, such as during periods of physical fatigue. During intense physical exercise, central nervous system arousal increases, towards an optimal level, after which any further increase in activation affects performance negatively, causing results to return to resting values (Hüttermann & Memmert, 2014). This trend is known as the Yerkes-Dodson law, or the inverted-U curve (Yerkes & Dodson, 1908). Further, when combining physically fatiguing exercise with a cognitive task, performance on the cognitive task may fall below even resting values, resulting in an inverted “J” curve, (as opposed to an inverted-U), and negatively affect performance on the cognitive task (McMorris, Hale, Corbett, Robertson, & Hodgson, 2015). The effects of physical fatigue have been reflected by deleterious performance after exercise above 80% VO_2 max during reaction time and short-term memory tasks (Féry et al., 1997), and Stroop task performance (Labelle et al., 2014). However, others have either found no effect of physical fatigue on cognition, or have found facilitating effects of fatiguing exercise on cognition (Audiffren et al., 2008; Davranche et al., 2014). Evidently, there are notable inconsistencies in the literature concerning the effects of fatiguing exercise on cognition. In one meta-analysis, only 41% of studies measuring cognition following fatiguing exercise administered and reported VO_2max values (Lambourne & Tomporowski, 2010). This is problematic, as physically fatiguing exercise may not produce the same effects in highly fit individuals (Shvartz and Reibold category 4.5; average-good) as compared to less fit individuals (Shvartz and Reibold category 2; poor) (Hüttermann & Memmert, 2014). Further, exercise sessions less than 11 minutes had negligible effects on cognitive performance, suggesting that short exercise sessions may not achieve a level of fatigue that would reflect the inverted-J trend (Chang, Labban, Gapin, & Etnier, 2012). Additionally, the timing of test administration appears to be a significant moderator, with the greatest effect sizes observed with tests completed within 0-10 minutes following exercise completion, after which smaller effects are observed (Chang et al., 2012). Therefore, a cognitive task must be chosen that can be appropriately completed within the 10-minute time frame for best results. Finally, tasks such as attention, intelligence, executive function, reaction time, and memory all reported widely different effects following fatiguing exercise (Chang et al., 2012). Therefore, the specific task used to assess the cognitive effects of a fatiguing exercise must be chosen carefully.

Other populations which exhibit altered executive function (i.e., older adults or those with concussion) demonstrate impaired collision avoidance behaviours, having more collisions, and scoring poorly on tests of visual perception and executive function (Uc et al., 2006; Baker & Cinelli, 2014). These changes in collision avoidance ability suggest that altered executive function reduces an individual's ability to effectively interpret and utilize visual information required to safely navigate an environment. Making judgements of passability regarding a closing aperture requires executive function to integrate visual perceptual information, and therefore it may be that collision avoidance behaviours in physically fatigued individuals may be impaired. This could result in a potential collision or bodily injury. Therefore, the purpose of our study was to determine if crossing a closing aperture is affected by physical fatigue. Based on cognitive embodiment literature suggesting perceptions of action capabilities can be affected by a perceived increased cost in achieving a goal, it was hypothesized that individuals' perceptions of aperture passability would be negatively affected by fatigue. This effect would be reflected by more conservative aperture crossing behaviours as they avoided a collision with the closing aperture. Further, the response time required to indicate whether an aperture was passable or not would increase following physical fatigue, based on increases in reaction time reported in the literature.

3.2. Methods

3.2.1. Participants

Recreationally active young adults (n=13; 8 women, 5 men; 23.5±1.9 years) with an average height of 172 ± 12.7 cm and weight of 64.9 ± 7 kg (females) and 85.6 ± 12 kg (males) were recruited to participate. Participants were included if they had normal or corrected-to-normal vision (and thus wore contact lenses during testing) and had no injuries that would prevent them from safely completing the protocol. Additionally, participants were included if they considered themselves able to cycle for 45 minutes at moderate to high intensity. Participants were excluded if they had participated in sport in a varsity level of competition or higher in the past five years. This study was approved by the Research Ethics Board of the local university (REB #5764).

3.2.2. Protocol

Prior to beginning the study, participants provided informed consent in compliance with the university ethics board, as well as a health history questionnaire and the Get Active Questionnaire as a pre-screening to exercise and to determine any contraindications to participation. Participants visited the laboratory on four separate occasions with at least 5 days between visits. Participants completed an initial familiarization session, where they were given the opportunity to wear the HTC Vive™ head-mounted display (HMD) and freely explore the simulated virtual reality (VR) environment. Additionally, a maximal incremental cycle ergometer test was conducted to determine maximal oxygen consumption (VO_2 max). The second session served as a confirmation session to confirm the appropriate exercise intensity (i.e., cycling wattage) for the exercise session, which was based on the ACSM cycle ergometry equation (equation provided below), calculated using participant's VO_2 max. During the third and fourth sessions, participants either completed a physically fatiguing cycling protocol with a VR task pre-test and post-test, or the control session, which consisted of a VR task pre-test and post-test, separated by a period of rest equal to the amount of time spent exercising on the exercise day (approximately 45 minutes). The exercise and control days were counterbalanced between participants. For the exercise and control days, participants were asked to avoid drinking any caffeinated beverage on the day of their testing sessions. Additionally, participants completed a food log of their food intake 24 hours leading up to their first laboratory visit, and were provided with this log 24 hours prior to subsequent sessions, with instructions to keep food intake consistent. This information was used to ensure participants kept their macronutrient intake consistent between experimental sessions.

3.2.3. Experimental Design

Aperture crossing task

The closing gap aperture crossing task was designed using Unity software, and was sampled at 90Hz. The program simulated the inside of an industrial building with a set of large factory doors (4m aperture width, 4.3m tall; Figure 1), located 5 meters from the participants' starting location, with a goal in the shape of a square on the floor located 1 meter beyond the doors (Figure 2). Following a familiarization period, participants completed 5 unobstructed real-walking trials of 7m with no VR environment changes. These trials were to determine each participant's preferred walking speed, which was used in the experimental trials to normalize door closure velocity. All following trials were completed using joystick-controlled locomotion, set at each participants preferred walking speed. Participants pressed a trigger on a handheld joystick to initiate movement and would move forward towards the aperture at a speed equal to their average walking speed. To terminate movement, participants would release the trigger. Only forward movement was possible; steering or backwards movement was not possible. Participants were instructed to travel (via joystick) to the end goal, and avoid contact with the closing aperture. Once participants had travelled 1m from their starting location, (i.e., 4m from the doors), the doors began closing at one of seven different speeds. Closing speeds were determined by a multiplication factor of each participant's average steady state walking speed (i.e.,, closing rate = walking speed * 1.2, 1.1, 1.0, 0.9, 0.8, 0.7, or 0.6), such that during the 1.2*walking-speed condition, the doors closed fastest (120% preferred walking speed). Participants completed 6 trials of each of the 7 closing rates, for a total of 42 randomized trials. Position data of the participants' head in space was recorded throughout the trials by the HTC Vive™ HMD to determine if the participant passed through the aperture or not, and their position relative to the aperture when a stop decision was made.

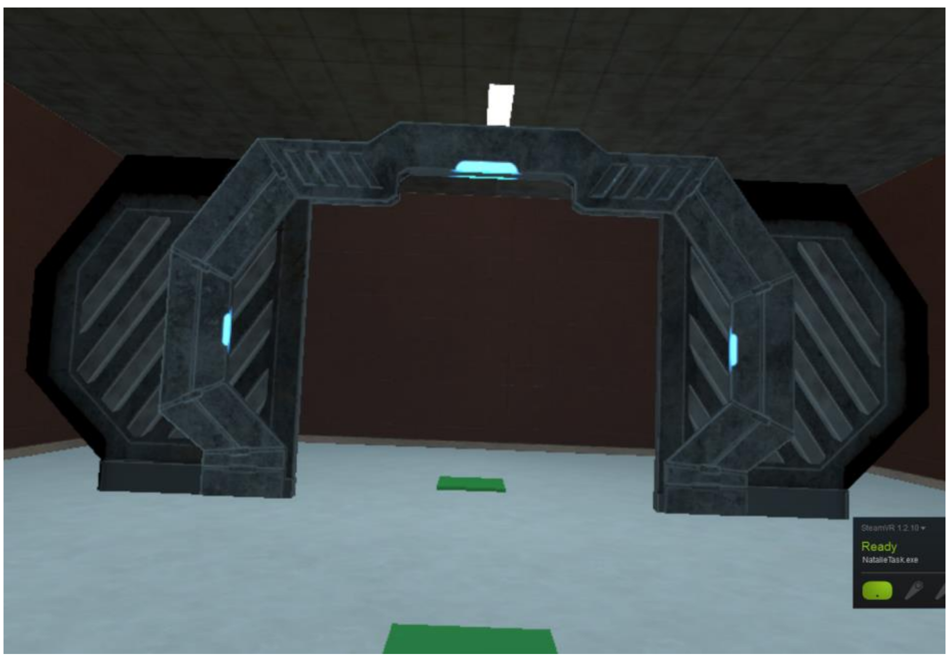

Figure 2: Simulated VR environment showing doorway, starting goal, and end goal

Familiarization session:

To ensure comfort with VR immersion, participants were outfitted with the HTC Vive™ HMD, immersed in the VR environment, and given time to walk around and explore. Following familiarization, participants completed 5 unobstructed steady-state walking trials along the 7m path with no changes to the VR environment. These trials were used to establish an average steady-state walking speed for each participant, and normalize door closure speed. Following the VR familiarization, participants performed the VO_2 max test using a cycle ergometer (Velotron, Racemate Inc, Seattle, Washington), with continuous recording of oxygen consumption using an online breath-by-breath gas collection system (MAX II, AEI technologies, PA, USA). Rate of perceived exertion (RPE) was recorded every four minutes throughout the test. Participants wore a heart rate monitor that recorded heart rate every two minutes throughout the test, and at cessation of exercise. To begin the maximal cycling protocol, participants completed a five-minute warm up at a self-selected pace (suggested cadence was between 70 and 90rpm), at a resistance set at 50W. Thereafter, participants continued cycling at their self-selected pace, and maintained this pace for as long as possible. Resistance began at 50W, and increased by 15W/min incrementally for all participants until participants' cycling cadence fell below 60rpm for more than 5 seconds. Participants were verbally encouraged throughout the test to provide a maximal effort. Following termination of exercise, participants completed a 5-minute cool down at a self-selected cadence at a resistance of 20W. 11 of the 13 participants reached plateau during the VO_2 max test, determined by a change in VO_2 less than 1.35 ml/Kg/min between the last two recordings taken before volitional exhaustion (all 13 reached plateau using 1.5 ml/Kg/min as threshold).

Confirmation session:

Recent research by Kier and colleagues (2018) suggests that merely estimating 80% VO_2 max from the wattage maximum obtained in the ramp-incremental cycle ergometer VO_2 max test is inaccurate when assigning wattage workload in constant-intensity exercise. Therefore, the metabolic equation from ACSM cycle ergometry predictive equations was rearranged to estimate wattage at 80% VO_2 max, specified as:

$$W = \left(\frac{(((VO_2max \times 0.8) - 7) \times\ kg)}{6}\right)$$

Participants cycled at a self-selected cadence (approx. 75rpm) at the calculated wattage until steady-state was reached (approx. 6 minutes), with continuous recording of oxygen consumption measured by a metabolic cart. Participants' oxygen consumption at steady state was compared to 80% of their recorded VO_2 maximum, and adjusted by $\pm$ 5 watts if 80% was not achieved. This process was repeated until the appropriate wattage that corresponded to 80% VO_2 max was achieved. The final wattage determined was then recorded for use during in the exercise session. Following the confirmation of work load, participants were given time for a cool down period if required.

Exercise session:

Participants first completed the VR protocol pre-test. Following the VR pre-test, the exercise protocol was completed. This protocol was adapted from the protocol used by Bentley and colleagues (2000), which elicited physical fatigue in 42 minutes of exercise. The workload wattage determined in the confirmation session was used as a normalized work rate for each participant. Participants warmed up for 5 minutes at 50W resistance, then complete 30 minutes of cycling at 80% VO_2 max, at a self-selected pace. Following this, participants were allowed 5 minutes of rest, and then completed 4, one-minute sprints at 110% of the workload (i.e., wattage) associated with VO_2 max with one-minute rest in between sprints. RPE was obtained every 4 minutes throughout the fatiguing exercise protocol and after each sprint. Participants were allowed water whenever needed. Immediately following termination of the test, participants completed the VR post-test.

Control session:

Participants arrived at the lab on the control experimental day and completed the VR pre-test and post-test identical to the exercise session, with 42 minutes of rest in between sessions.

3.2.4. Data and Statistical Analysis

Data were sorted according to aperture condition (0.6 to 1.2x walking speed) for pre-control (pre-CT), post-control (post-CT), pre-exercise (pre-EX), and post-exercise (post-EX). The proportion of trials (out of 6 per condition) where the participant passed through the doors (0) or stopped (1) was recorded for each aperture closing speed during all four testing timepoints. Participant location (relative to the doors) at the moment they stopped their approach was determined by the HMD head position. If the participant passed through the aperture, distance was recorded as a 0. For each of the 4 test blocks per participant, the proportion of trials in which a stop occurred within each aperture closing condition was plotted and fit with a third order polynomial. The 50% Switch Point was then calculated from the polynomial (by solving for x where y=0.5), representing the relative aperture closing rate in which a change in behaviour occurred, or the aperture closing speed in which participants passed through the aperture and stopped an equal amount of times. No feedback was given regarding aperture passage success, as the objective was to compare passability judgements pre-and-post control or fatigue, regardless of the “correctness” of decision. Technically, a “correct” decision was calculated using average shoulder width as a 50% switch point less than *0.9*walking-*

speed (see "Justification for study 2", however this threshold would be different for each participant based on their individual shoulder width.

The 1.0x walking speed condition was considered the most challenging, as it was the slowest moving aperture speed that was still impassable (i.e.,, doors would be completely closed at the time when the participant was standing in front of them). Therefore, the TTC values for this condition were chosen for analysis. The average TTC, or the remaining time before the participant would have collided with the doors was calculated using participant's head position relative to the doors at stop (m) divided by their steady-state walking speed (m/s). Both a 50% Switch Point and a TTC value were calculated for each participant, for each testing block (pre-CT, post-CT, pre-EX, post-EX).

The 50% Switch Points and TTC values were compared using 2-way (test day x time point) repeated measures ANOVAs to determine whether physical fatigue had an effect on passability judgements, or on the time required to collect visual information and make a decision. To determine if there was a learning effect across the four test points (between two test days) regardless of condition (control or exercise), the 50% Switch Points were organized chronologically and analyzed using a one-way repeated measures ANOVA. Results were reported as average ± standard deviation; p values < .05 were accepted as significant. Cohen's F values were provided as a measure of effect size (low: 0.1; medium: 0.25; high: >0.4).

3.3. Results

Regarding the VO_2 max test values, the males had an average VO_2 max of 40.3 ± 2.6 ml/kg/min, and the females 37.01 ± 3.8 ml/kg/min. The 2-way repeated measures

ANOVA revealed no significant differences in the 50% Switch Point between Pre-CT ($\bar{x}$ = 0.86 ± 0.05), Post-CT ($\bar{x}$ = 0.87 ± 0.06), Pre-EX ($\bar{x}$ = 0.87 ± 0.07), or Post-EX ($\bar{x}$ = 0.86 ± 0.06) ($F_{(1,12)}$=1.04, *p*=.33, *f*=.29) (Figure 3). Further, when the 50% Switch Points were organized and compared in order of exposure, there was again no significant effect ($F_{(3,36)}$=0.268, *p*=.85, *f*=.15). When comparing the TTC values between timepoints, the 2-way repeated measures ANOVA revealed a significant interaction, such that TTC was significantly lower during the post-test on the exercise day ($\bar{x}$ = 1.16 ± 0.26 s; $F_{(1,12)}$=11.07, p=.006, *f*=0.0.96), compared to the control pre-test ($\bar{x}$ = 1.33 ± 0.25 s) and post-test ($\bar{x}$ = 1.45 ± 0.3 s), and the exercise day pre-test ($\bar{x}$ = 1.4 ± 0.23 s). Finally, the average percent of age-predicted heart rate reached a maximum of 93% during the task (Figure 5a), and average rate of perceived exertion reached a maximum of 19 during the task (Figure 5b).

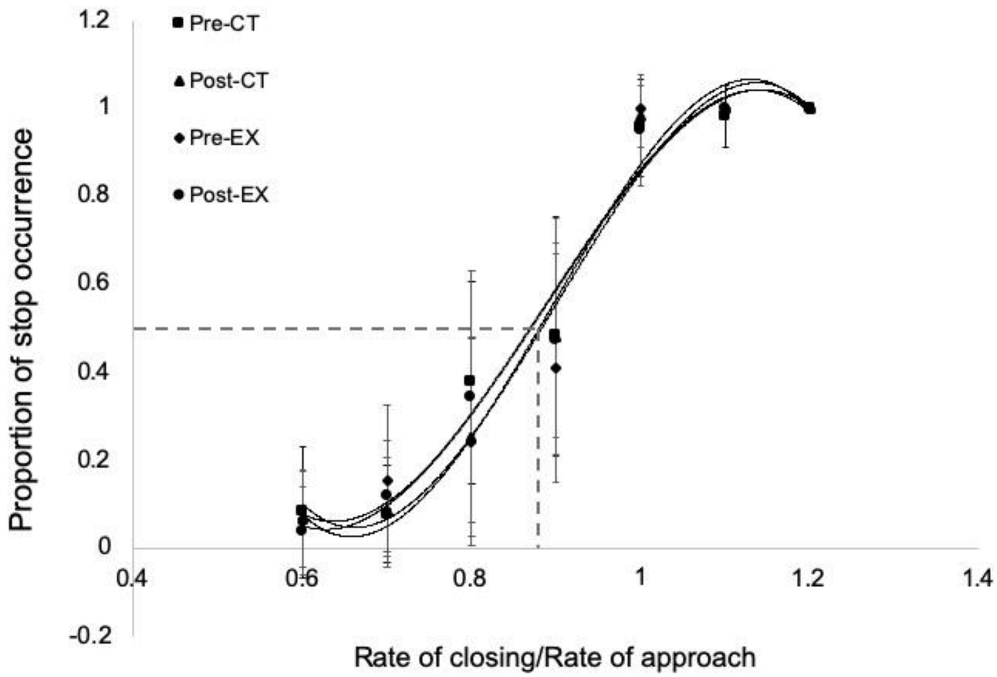

Figure 3: Average proportion of trials (± SD) for each timepoint (Pre-CT, Post-CT, Pre-EX, Post-EX) where participants did not pass through the closing aperture for each condition (rate of closing/rate of approach; 0.6-1.2*approach speed), with a 3rd order polynomial. 50% proportion identified where each switch point is.

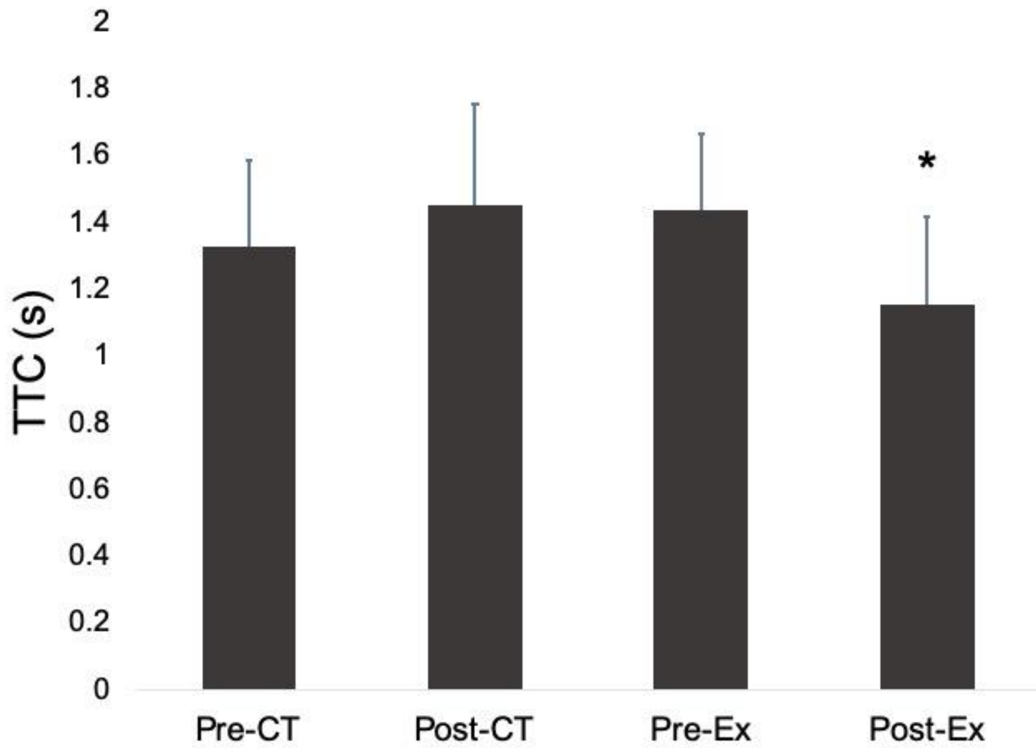

Figure 4: Mean time-to-contact (TTC) and standard deviation bars for 1.0*walking speed at four timepoints (Pre-CT, Post-CT, Pre-EX, Post-Ex). * indicates significant difference at $p<.05$.

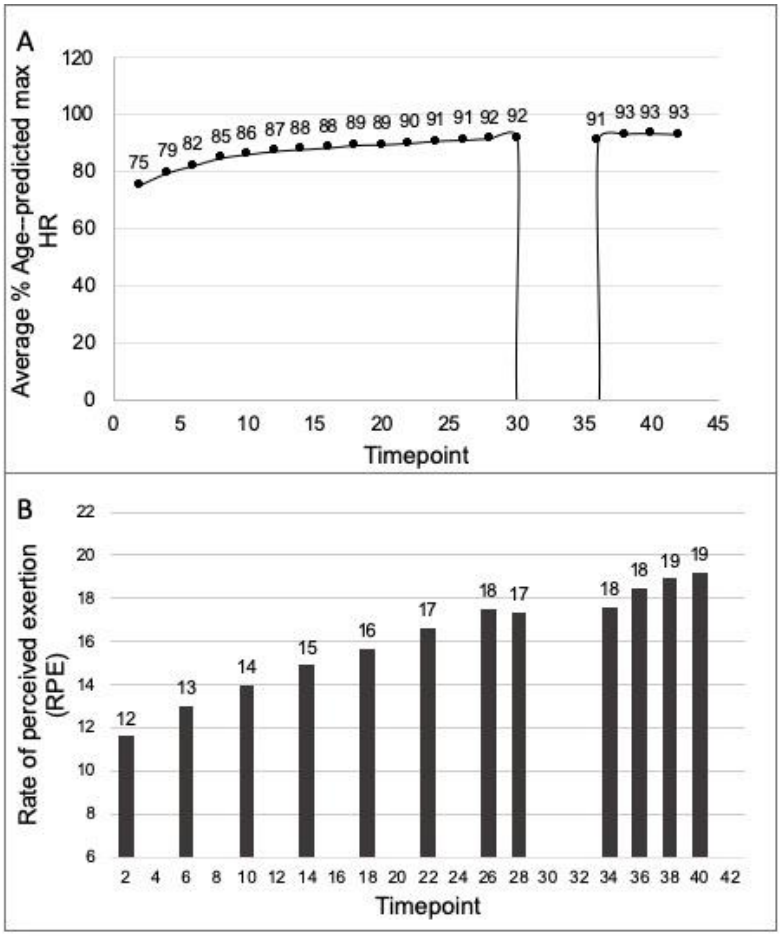

Figure 5: A) Average percent of age predicted maximum heart rate (HR) across each test point, and at the end of each sprint interval. B) Average rate of perceived exertion (RPE) at each test interval, and after each sprint interval.

3.4. Discussion

The purpose of this study was to determine if physical fatigue affects crossing decisions during a closing gap VR task. It was hypothesized that the 50% Switch Point and TTC would be affected, where Switch Point would be lower (i.e., stopping for more passable aperture conditions), and TTC would be smaller (i.e., longer decision-making time). Perceptual judgements (50% Switch Point) were not affected, however the time required to carry out decisions (TTC) was significantly delayed after physically fatiguing cycling exercise. By using joystick-controlled locomotion, we removed any confounding variable that could arise from physically completing aperture crossing after physically fatiguing exercise. Joystick-controlled locomotion thus allowed analysis of decisions made primarily based off visual perceptual information.

The main variable of interest in this study was the 50% Switch Point. The physically fatiguing exercise had no effect on the 50% Switch Point at any of the testing blocks (pre-CT, post-CT, pre-EX, post-EX) suggesting that participants' perceptions of their own action capabilities (i.e., affordances) and tau-coupling abilities were not affected by physical fatiguing cycling exercise. The lack of effect is in line with previous visuomotor task performance following fatiguing exercise, where participants demonstrated no negative changes to accuracy on a line matching task after treadmill exercise which increased in speed and grade (Mcglynn, Laughlin, & Bender, 1977). When wall climbers were asked to make perceptual judgements regarding their maximum reaching height before and during successive fatiguing wall climbs, neither their perceived or actual maximum reaching height decreased after physically fatiguing exercise (Pijpers, Oudejans, & Bakker, 2007). The results for this study may suggest that perceptual abilities, specifically perception of affordances (i.e., action-capabilities; 50% Switch Point), are not affected by the physically fatiguing exercise competed during this study

Contrary to the 50% Switch Point results, TTC was significantly lower after physically fatiguing exercise compared to all other test blocks. Lower TTC values suggests that participants stopped significantly closer to the aperture on average, suggesting an increase (i.e., slower) in response time, which is consistent with many previous studies that evaluated response time performance on visuomotor tasks following physical fatigue (Ando et al., 2012; Bender & McGlynn, 1976; Féry et al., 1997; Labelle, Bosquet, Mekary, & Bherer, 2013; McMorris & Keen, 1994). Labelle and colleagues (2013) reported increased reaction time during a modified Stroop task following 6.5 minutes of cycling at 80% of peak power output, while Ando and colleagues (2012) reported significantly increased premotor time on a visuomotor task following 10 minutes of cycling at 75% VO_2 peak. Both of these results were from visuomotor task performance in individuals with cardiovascular fitness categorized as fair (average VO_2 of 38.33 mL/Kg/min among 10 men and 11 women; Labelle et al., 2013) and good (VO_2 peak of 45.0 ml/Kg/min in a population of 11 males; Ando et al., 2012) as per ACSM treadmill VO_2 normative values (American College of Sports Medicine, 2013).

When considering a possible explanation for why the 50% Switch Point was not affected, but TTC showed detrimental changes, it could be that participants were not adequately fatigued. The fatiguing cycling protocol chosen for this study was adapted from Bentley and colleagues (2000), who measured central and peripheral fatigue kinetics during intense constant-load cycling exercise to establish neuromuscular fatigue. Their physical fatiguing-inducing cycling protocol satisfied the necessary criteria for the present study, which was: 1) to use a fatiguing cycling protocol that could induce physical fatigue which lasted beyond 15-20 minutes post-exercise (i.e., the time required to complete the VR post-test); and 2) to induce physical fatigue in a standardized timeframe, so that the pre- and post-test on both the exercise and control days were completed with a controlled amount of time between tests. Therefore, the protocol in the current study was chosen to address inconsistencies in previous literature regarding the effects of fatiguing exercise on cognitive performance as per the recommendation of Chang, Labban, Gapin, and Etnier (2012). In the current study, the neuromuscular fatigue measurements collected by

Bentley and colleagues (2000) were not replicated, however the intense constant-load cycling protocol was reproduced closely. Further, indirect measures of fatigue collected during this study (i.e., RPE; HR) reflect moderate through high levels of exertion over the duration of the cycling protocol (Figure 5). Based on a close replication of the protocol, and the indirect measures of fatigue that were collected during this study, it is reasonable to assume that the levels of fatigue achieved in the current study were similar to that reported by Bentley and colleagues (2000). Therefore, it is unlikely that the 50% Switch Point results were due to inadequate levels of fatigue.

Further, it must be considered that perhaps the VR world itself influenced the 50% Switch Point results. However, the 50% Switch Points observed in the current study (0.85-0.86*walking speed) are consistent with previous work using the same paradigm with non-fatigued healthy young adults (0.85*walking speed; determined in Study 1). This similarity provides support for the conclusion that at all test points, the participants of the current study behaved consistently with non-fatigued participants. Therefore, the VR world had no influence on the findings.

Finally, one possible explanation could be that learning occurred across the four timepoints, ultimately confounding any differences that may have occurred for those who completed the fatiguing exercise test day second, following the control day. However, when analyzing the 50% Switch Point when test points were organized in chronological order, the lack of difference in the 50% Switch Point across the blocks were maintained. Thus, a learning effect does not explain the lack of difference in the 50% Switch Point following the fatiguing protocol.

The present study data only specified two variables: passability judgements (i.e., 50% Switch Point) and TTC. As such, there is insufficient data to determine the physiological mechanism behind the findings of this study. Further, a laboratory model that reliably links physical fatigue to cognitive performance has yet to be developed (Lambourne & Tomporowski, 2010). The 50% Switch Point variable is based on perception informing action, assessed via a simple go/stop button press, which inherently bypasses the cognitive component of the perception-action cycle (Figure. 2). Based on the fact that there was no difference in the 50% Switch Point across the four testing blocks, it appears that perception-action coupling may be unaffected by physical fatigue. However, a dichotomous decision about action capabilities may not be the best way to assess changes to perception-action coupling following physical fatigue. The aspect of the task that required the most cognitive processing and motor planning prior to action (i.e., TTC) was negatively impacted by physical fatigue. The lower TTC values following exercise suggest that physical fatigue affects the link between cognition and action in the perception-action cycle (Figure 6).

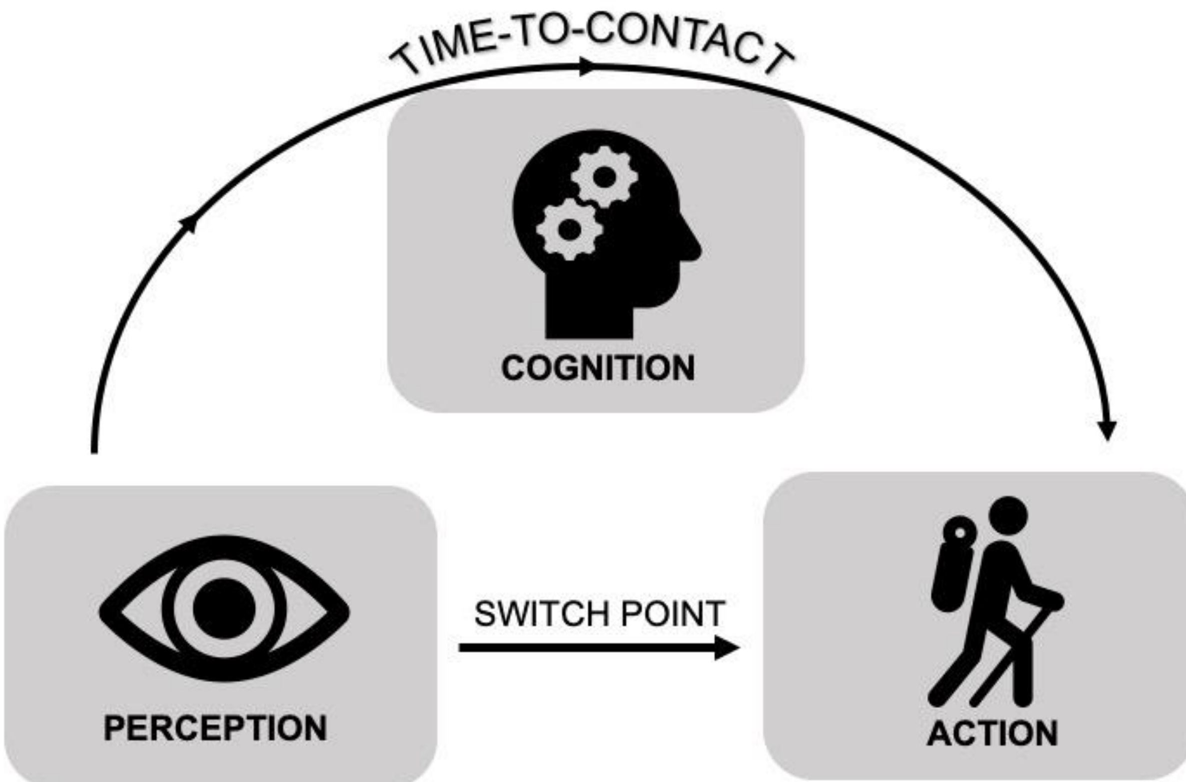

Figure 6: Refined perception-action cycle. There are two ways of acting on perceptions; the direct link (i.e., 50% Switch Point) and with cognitive influence (time-to-contact; TTC).

Therefore, when speculating on a potential mechanism to explain the changes to neurological control following exercise, a few possibilities exist. The most plausible hypothesis to explain the findings of the current study, is that following the fatiguing exercise, brain glycogen was depleted, which in turn impaired executive functioning. The functioning of the central executive is in part determined by levels of brain glycogen, specifically when glucose quantities in the brain are low (Gailliot, 2011). The central executive is metabolically expensive, and thus requires large quantities of glucose compared to other cognitive processes. Therefore, following physically fatiguing exercise, individuals may have performed the subsequent VR post-test on a reduced amount of brain glucose, which potentially impaired executive function (Gailliot, 2011), and may explain why the 50% Switch Point (a dichotomous perceptual task), was unaffected, but TTC (a process requiring more cortical areas and processing, i.e., the central executive), reflected detrimental effects. Another factor that may provide support for this hypothesis is depletion of the central executive, specifically self-regulation. Self-regulation refers to the capacity to alter inner states or responses (i.e., actions, thoughts, feelings, and task performances; Bray, Martin Ginis, Hicks, & Woodgate, 2008). Individuals who aim to override an impulse (i.e., the urge to stop exercising, food cravings) draw on a personal resource known as self-regulatory strength. Self-regulatory strength can be depleted during periods of heavy self-regulation, and is not readily replaced. Interestingly, one function of the central executive is persistence at physical exercise, which requires self-regulation as an individual maintains a constant drive to continue moving and resist giving up (Gailliot, 2011). This task of physical persistence thus also requires brain glycogen (Baumeister et al., 1998), and may contribute to the depletion of brain glycogen following physically fatiguing cycling exercise, resulting in delayed responses during the closing-gap aperture crossing task.

Another explanation is the hypofrontality hypothesis (Dietrich, 2003), which is based on the knowledge that the brain has limited resources, but maintenance of high-intensity exercise taxes the motor areas of the brain. This hypothesis predicts deactivation in prefrontal cortex during strenuous exercise, and the brain reacts by modifying its resource allocation (Dietrich, 2003). For example, significantly longer premotor time was recorded during a button-press simple visual reaction time task while cycling at 75% peak

VO_2, potentially indicating deactivation in the prefrontal cortex (Ando et al., 2012). while deactivation in the prefrontal cortex may explain the reduction in TTC observed in the current study, it does not account for the lack of difference found in 50% switch point.

Based on previous findings in Study 1, performance on the VR closing gap aperture crossing task using a joystick is similar to when individuals perform real-walking with an HMD, given a small margin of error. It was found that the 50% Switch Point varied by up to 0.5*walking speed between the locomotion interfaces due to sensory integration differences. Therefore, it may be that individuals' passability judgements on the current task may vary slightly if completed in a real-walking scenario. The findings in the current study provide deeper understanding of the cognitive effects of physical fatigue, as well as an understanding of the way in which perception and cognition are differentially affected by potential reductions in brain glucose. This study did not allow for consideration of whether the negative effect on response time (i.e., TTC) is transient, or maintained in the hours following termination of exercise. In the future, the closing gap aperture crossing task should be performed at more timepoints in the hours following termination of exercise.

Conclusion

In conclusion, this study aimed to understand the physiological responses to exercise that have implications for cognitive function, specifically executive function and decision-making. Perceptions of action capabilities were not affected by physical fatigue, which is consistent with other fatigue literature demonstrating no effect on general perceptual abilities. However, TTC was significantly reduced following physically fatiguing cycling exercise, suggest that processes requiring more cortical areas and processing (i.e., response time; TTC) are more detrimentally affected by physically fatiguing cycling exercise compared to dichotomous visuomotor tasks (i.e., passability judgements). This study aimed to address inconsistencies in the literature regarding cognitive performance following physically fatiguing exercise, to improve the significance and comparability of the current results. Future research should assess perceptions of affordances in a manner not limited to a dichotomous decision, which may provide deeper understanding of potential changes in decision-making capabilities following physical fatigue.

CHAPTER 4: GENERAL DISCUSSION

The overall objective of this thesis was to understand factors that affect decision-making on a closing-gap aperture crossing task in virtual reality (VR). Using a VR platform is advantageous, as it allowed us to observe collision avoidance behaviours safely and under different types of locomotion. Study 1 observed aperture crossing behaviours between two locomotion interfaces (real-walking and joystick-controlled locomotion). The objective was to determine if joystick-controlled locomotion produced the same aperture crossing behaviours in VR as real walking, which would make it a viable tool to study the effects of physical fatigue on decision-making in Study 2. The results of this study would provide deeper significance to the results of study two and remove locomotion interface as a confounding variable. Interestingly, the results from Study 1 had fundamentally significant implications for multisensory integration and collision avoidance in and of itself. We determined that when using joystick-controlled locomotion, the sensory conflict introduced by incongruent somatosensory and vestibular information may cause individuals to underestimate the distance between themselves and the aperture, resulting in perception of slightly more aperture conditions as passable compared to when real-walking (i.e., an increase in 50% switch point). With the understanding of the slight change in aperture crossing behaviour when using joystick-controlled locomotion, Study 1 determined that young adults can use vision alone to avoid obstacles in the environment in absence of supporting sensory information. Further, Study 1 determined a critical point for closing gaps for both the real-walking and joystick-controlled locomotion interfaces. The critical point metric allows these results to be compared to past collision avoidance work which used critical point to determine action-capabilities. In Study 2, the closing-gap aperture crossing task was utilized with the understanding that joystick-controlled locomotion can be used to study collision avoidance behaviour via switch point, but there is a margin of error to consider before comparing these results to other aperture crossing studies.

The purpose of Study 2 was to understand how physical fatigue affects cognitive performance during collision avoidance, specifically a closing-gap aperture crossing task. Fatiguing exercise is interesting because of the wealth of literature identifying deficits in cognitive psychomotor performance as a result of fatigue (Chang et al., 2012; T. McMorris et al., 2005). However, there are a wide range of inconsistencies in fatiguing exercise literature that this study aimed to address and improve. The same dependent variables as Study 1 were employed, assessing which aperture closing condition elicited a change in behaviour (i.e., 50% switch point), and how close participants were to the aperture when they made a stop decision (i.e., TTC). Decision-making abilities (50% switch point) were not affected by physical fatigue in recreationally active participants, only the time required to make decisions (TTC) was affected. Therefore, simple dichotomous decision-making tasks are not affected by fatigue because they are based solely on perceptions, whereas carrying out these decisions requires more cognitive resources (i.e.,, cortical areas), and therefore are subject to the effects of physical fatigue. In everyday situations where people find themselves in a physically fatiguing scenario, our conclusions would suggest that they are not at risk of making unwise or unsafe decisions, only that producing these decisions may be delayed, which could be a safety concern for these individuals. Study 2 elucidated how recreationally active individuals respond to physical fatigue during collision avoidance, specifically crossing closing gaps. Further, Study 2 speculated on a neurophysiological mechanism causing delayed decision-making reported in the literature, suggesting that depleted brain glucose attenuates synaptic transmission in the cortical areas required for decision-making (Ando, Kida, & Oda, 2001; Gailliot, 2011; Terry McMorris & Keen, 1994).

A limitation for both Study 1 and Study 2 is that the HTC Vive™ HMD does not provide peripheral field of view to the wearer, and thus participants did not have visual information regarding their body location. Therefore, visual information from the environment is not entirely veridical. This limitation exists in all VR research using the HMD, therefore future research could study aperture crossing behaviours using other VR platforms such as the CAVE (Radwin, Chen, Ponto, & Tredinnick, 2013). One limitation for Study 2 is that no data was collected to determine if the effects of physical fatigue on decision-making time are transient. Therefore, future research should re-test participants at more intervals following post-exercise (i.e., one hour, 6 hours, 24 hours, etc.). Additionally, as mentioned in Study 2, our data was insufficient to determine a physiological mechanism which explains the results. Therefore, future research should evaluate decision making (i.e., switch point and time-to-contact) during a closing-gap aperture crossing task combined with neuroimaging techniques, which may improve understanding of the neurophysiological mechanisms influencing perception, cognition, and action following fatiguing exercise. It is important to note that the applications of the results of Study 2 are limited by the characteristics of the chosen sample. We tested recreationally active individuals, but experienced athletes do not exhibit similar deleterious performance in response to physically fatiguing exercise (Hüttermann & Memmert, 2014). Therefore, we are limited in the ability to apply these results as possible explanations for the mistakes and unsatisfactory performance exhibited by athletes during “clutch” sports scenarios. Conversely, in Study 1 where healthy young adults performed almost as well on the closing-gap aperture crossing task using joystick-controlled locomotion compared to real-walking, other populations may not be able to complete the task as well. Individuals who have reduced visual function, or are unable to reweight sensory input due to sensory conflict may not exhibit the same aperture crossing behaviours. Finally, in future research, different types of fatigue should be studied (i.e., mental fatigue, sleep deprivation) to understand how aperture crossing behaviours can be affected by other sources of fatigue. The ability to compare aperture crossing behaviours under different types of fatigue will allow us to determine if the behaviours recorded in the current research result specifically from the effects of physical fatigue, or if there are other factors that must be considered.

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APPENDIX A**: PARTICIPANT EXERCISE DATA:**

Heart rate (HR; bpm), percent of age-predicted maximum heart rate (% APMHR), and rate of perceived exertion (RPE) at each test point during 42 minutes of constant-load fatiguing exercise (30 minutes cycling, 5 minute rest, then 4, one-minute sprints).

	F1			F2			F3		
Time	**HR (bpm)**	**% APMHR**	**RPE**	**HR (bpm)2**	**% APMHR3**	**RPE4**	**HR (bpm)5**	**% APMHR6**	**RPE7**
2	142	71.4		145	74.0		147	74.6	
4	150	75.4	9	148	75.5	11	146	74.1	12
6	155	77.9		156	79.6		156	79.2	
8	163	81.9	13	170	86.7	13	157	79.7	13
10	170	85.4		179	91.3		157	79.7	
12	170	85.4	14	182	92.9	15	161	81.7	13
14	172	86.4		182	92.9		163	82.7	
16	175	87.9	17	185	94.4	16	166	84.3	13
18	178	89.4		188	95.9		165	83.8	
20	170	85.4	18	188	95.9	17	165	83.8	14
22	170	85.4		188	95.9		169	85.8	
24	182	91.5	18	190	96.9	18	169	85.8	16
26	182	91.5		191	97.4		167	84.8	
28	182	91.5	18	191	97.4	19	170	86.3	17
30	182	91.5	18		0.0		171	86.8	17
32		0.0			0.0			0.0	
34		0.0			0.0			0.0	
36	173	86.9	19	190	96.9	19	176	89.3	17
38	182	91.5	19	194	99.0	20	175	88.8	18
40	182	91.5	19	190	96.9	20	175	88.8	19
42	183	92.0	19			20	171	86.8	19

F4			F5			F6		
HR (bpm)8	% APMHR9	RPE10	HR (bpm)11	% APMHR12	RPE13	HR (bpm)14	% APMHR15	RPE16
156	81.7		109	55.3		150	76.1	
162	84.8	13	150	76.1	13	148	75.1	9
163	85.3		153	77.7		151	76.6	
171	89.5	13	163	82.7	13	155	78.7	13
174	91.1		161	81.7		155	78.7	
177	92.7	14	164	83.2	13	160	81.2	14
178	93.2		165	83.8		161	81.7	
177	92.7	15	168	85.3	13	162	82.2	16
179	93.7		169	85.8		165	83.8	
186	97.4	15	171	86.8	15	166	84.3	16
184	96.3		173	87.8		167	84.8	
183	95.8	16	175	88.8	16	167	84.8	17
186	97.4		175	88.8		167	84.8	
189	99.0	16	175	88.8	17	168	85.3	17
192	100.5	17	175	88.8	18		0.0	
	0.0			0.0			0.0	
	0.0			0.0			0.0	
184	96.3	16	182	92.4	18	157	79.7	14
193	101.0	17	182	92.4	19	171	86.8	17
193	101.0	17	182	92.4	19	174	88.3	19
197	103.1	18	185	93.9	19	175	88.8	19

F7			F8			9		
HR (bpm)17	% APMHR18	RPE19	HR (bpm)20	% APMHR21	RPE22	HR (bpm)23	% APMHR24	RPE25
157	79.7		165	83.8		172	87.3	
165	83.8	16	173	87.8	12	180	91.4	13
168	85.3		178	90.4		186	94.4	
170	86.3	16	183	92.9	14	187	94.9	13
173	87.8		186	94.4		186	94.4	
173	87.8	17	188	95.4	15	188	95.4	14
175	88.8		187	94.9		190	96.4	
175	88.8	17	186	94.4	16	192	97.5	14
176	89.3		187	94.9		192	97.5	
178	90.4	18	185	93.9	16	192	97.5	14
177	89.8		188	95.4		193	98.0	
178	90.4	18	186	94.4	17	194	98.5	15
180	91.4		187	94.9		195	99.0	
180	91.4	19	187	94.9	18	197	100.0	17
	0.0					194	98.5	17
	0.0			0.0			0.0	
	0.0			0.0			0.0	
181	91.9	19	180	91.4	18	197	100.0	20
181	91.9	18	187	94.9	19	198	100.5	20
183	92.9	19	187	94.9	20	197	100.0	20
183	92.9	20	187	94.9	20	196	99.5	20

10			11				12	
HR (bpm)26	% APMHR27	RPE28	HR (bpm)29	% APMHR30	RPE31	HR (bpm)32	% APMHR33	RPE34
139	70.9		162	81.4		135	68.9	
147	75.0	12	170	85.4	11	140	71.4	9
158	80.6		171	85.9		140	71.4	
164	83.7	13	176	88.4	13	145	74.0	10
169	86.2		178	89.4		145	74.0	
170	86.7	16	181	91.0	14	146	74.5	11
173	88.3		181	91.0		146	74.5	
174	88.8	16	182	91.5	15	147	75.0	13
175	89.3		187	94.0		150	76.5	
176	89.8	17	186	93.5	16	150	76.5	14
179	91.3		187	94.0		152	77.6	
181	92.3	17	188	94.5	17	155	79.1	15
181	92.3		188	94.5		155	79.1	
181	92.3	18	190	95.5	19	156	79.6	16
183	93.4	18	192	96.5	19	160	81.6	16
	0.0			0.0			0.0	
	0.0			0.0			0.0	
170	86.7	16	196	98.5	20	165	84.2	17
186	94.9	19	192	96.5	20	165	84.2	18
188	95.9	20	190	95.5	20	165	84.2	18
						167	85.2	18

	13			
HR (bpm)35	**% APMHR36**	**RPE37**	**Average % APMHR**	**Average RPE**
136	69.0		75.3	
143	72.6	11	79.4	11.6
157	79.7		82.1	
158	80.2	12	84.7	13.0
162	82.2		86.0	
165	83.8	12	87.1	14.0
167	84.8		87.7	
167	84.8	13	88.3	14.9
169	85.8		89.2	
171	86.8	14	89.4	15.7
171	86.8		89.9	
171	86.8	16	90.7	16.6
172	87.3		91.0	
174	88.3	17	91.5	17.5
175	88.8	17	63.6	17.4
0	0.0		0.0	
0	0.0		0.0	
170	86.3	16	90.9	17.6
176	89.3	16	93.1	18.5
180	91.4	16	93.3	18.9
			93.0	19.2

APPENDIX B: INFORMED CONSENT

WILFRID LAURIER UNIVERSITY

INFORMED CONSENT STATEMENT

Title of Project: The effect of physical fatigue on decision-making during collision avoidance

Principle Investigator: Natalie Snyder, Master of Kinesiology & Physical Education
Email: snyd5380@mylaurier.ca
Supervisor: Dr. Michael Cinelli, Associate Professor, Kinesiology & Physical Education
Email: mcinelli@wlu.ca

INFORMATION

You are invited to participate in a research study. The purpose of this study is to determine the effect of physical fatigue on decision-making during collision avoidance. Approximately 15-18 participants will be tested from WLU's student population between the ages of 18 and 25.

Participants will fill out a health history questionnaire and a Get Active Questionnaire prior to participation to establish readiness to exercise and identify any contraindications to fatiguing exercise. You will be required to attend four testing sessions: a familiarization session, a confirmation session, an exercise session, and a control session. For each session, you will be requested to arrive in clothing suitable for exercising in. Additionally, you will be required to document your meals 24 hours prior to each session until the morning of the testing session, and match diet prior to the first day to each subsequent testing session.

During the familiarization session, 46 trials will be completed in virtual reality (VR), using a head-mounted display (HMD). The simulated VR world is an empty room with large doors at one end. 5 walking trials will be completed to establish average walking speed, followed by 21 trials of real-walking through apertures (i.e. the doors) closing at 7 different speeds. This will be followed by 21 trials of the same conditions, however joystick navigation will be used instead of real-walking. Participants will be instructed to approach the closing aperture at a constant speed and pass through it if they think they will fit. If not, they will stop their approach. Additionally, a maximal oxygen consumption (vo2) test will be conducted to normalize workload during the exercise session to each participant.

During the confirmation session, participants will cycle for 6-12 minutes using the metabolic cart to confirm appropriate exercise intensity to be used during the exercise session. During the exercise session, participants will complete a VR pre-test: 21 trials of joystick navigation through an aperture closing at 7 different speeds. Following this, the exercise protocol will be completed. Participants will warm up on the cycle ergometer, then complete 30 minutes of cycling at 80% VO2, at a self-selected pace. Participants will then cycle against no resistance for 5 minutes, then complete 4, one minute sprints at 110% VO2 max, with one minute in between each sprint. Heart rate and rate of perceived exertion (RPE) will be taken every 2 minutes for the entire test. Immediately following cessation of exercise, a VR post-test will be completed, identical to the VR pre-test. During the control session, participants will complete the VR pre-test and post-test, separated by 45 minutes of rest.

The expected duration of each session is approximately 90 minutes. This includes reading and

Participant initials: ___________

signing the consent form, filling out the questionnaire, completing the procedures, and rest periods.

RISKS

There may be a risk of muscle soreness, muscle weakness, or nausea following the exercise prescribed in this study. There may be a risk of boredom associated with this study. Rest periods may be taken as needed.

BENEFITS

Individuals will receive no direct benefits from this study, but will indirectly assist with understanding the effect of physical fatigue on decision-making during collision avoidance.

CONFIDENTIALITY

The identification of participants will be kept anonymous by a letter and number system understood only by the Co-Investigator and the Supervisor. Personal information about the participants and test results will be kept separately to ensure protection of privacy. The data will be kept for a period of 7 years and then erased or shredded.

CONTACT

If you have questions at any time about the study or the procedures, (or you experience adverse effects after participating in this study) you may contact the researchers, Natalie Snyder (snyd5380@mylaurier.ca), or Dr. Cinelli (mcinelli@wlu.ca) at 519-884-0710 ext. 4775. This project has been reviewed and approved by the University Research Ethics Board (**#5764**). If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Dr. Robert Basso, Chair, University Research Ethics Board, Wilfrid Laurier University, (519) 884-1970 ext. 4994 or rbasso@wlu.ca

PARTICIPATION

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study, every attempt will be made to remove your data from the study, and have it destroyed. You have the right to omit any question(s)/procedure(s) you choose.

FEEDBACK AND PUBLICATION

The results from this study will be presented at the International Society for Posture and Gait Research World Congress in Edinburgh, Scotland, June 2019. Results will also be prepared for publication following completion in 2019.

CONSENT

By signing this consent form, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities

Participant initials: __________

I have read and understand the above information. I have received a copy of this form. I have had the chance to ask any questions related to this study, to get answers to my questions, and any other details I wanted. I agree to participate in this study.

This project has been reviewed and received ethics clearance through the Research Ethics Board at Wilfrid Laurier University. I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact Dr. R. Basso, Chair of the Research Ethics Board, Wilfrid Laurier University, at 519-884-1970, extension 4994 if I have questions concerning my participation in the experiment.

Participant's signature_______________________________________Date _________________

Investigator's signature_______________________________________Date _________________

Participant initials: __________

APPENDIX C: HEALTH HISTORY QUESTIONNAIRE

Health History Questionnaire

We are interested in your personal history because it may help us to better understand the results of our study. Your answers to a few short questions will aid us in this effort. All answers will be kept strictly confidential. You may choose not to provide a response to any questions without penalty.

Demographics:

1. Age:___________
2. Year of Birth: ________ Month of Birth: _________
3. Height: _______________
4. Weight: _______________
5. Gender:_______________
6. Current Employment:____________________________

Vision:

7. A) Do you have:

Glaucoma . . . .NO / YES
Cataract(s) . . . .NO / YES
Macular degeneration . . . .NO / YES
Amblyopia/ Lazy Eye/ Binocular vision defect (i.e. turned down eye) ..NO / YES

B) Have you ever had eye surgery for:

Glaucoma . . . . .NO / RIGHT / LEFT Date:________________
Cataract(s) . . . . .NO / RIGHT / LEFT Date:________________
Macular degeneration . . . . .NO / RIGHT / LEFT Date:________________
Corneal/lens transplants . . NO / RIGHT / LEFT Date:________________
Laser eye surgery . . . . NO / RIGHT / LEFT Date:________________

C) Do you currently receive medical treatment for your eyes? . . . . NO / YES
If **YES**, what kind? ____
Patching/ Vision Therapy?____

D) Have you ever seen a doctor for an eye injury? . . . . NO / YES
Describe: ____

8. Have you ever been unconscious, had a head injury or had blackouts?
A) NO / YES
B) Cause: ____
C) Duration:____
D) Treatment: ____
E) Outcome:____

F) Year(s): ____

9. Have you been seriously ill or hospitalized in the past 6 months?
   A) NO / YES
   B) Cause:
   C) Duration:____

Do you have now, or have you had in the past :

10. a) A Stroke? b) Transient ischemic attack?	NO / YES NO / YES	When?
11. Heart disease?	NO / YES	Nature (MI, angina, narrowing of arteries):
12. High blood pressure?	NO / YES	Is it controlled?
13. Seizures?	NO / YES	Age Onset:______ Frequency:___________ Cause: Treatment:
14. Epilepsy?	NO / YES	
15. Frequent headaches?	NO / YES	Tension / migraine
16. Dizziness?	NO / YES	
17. Trouble walking? Unsteadiness	NO / YES	
18. Arthritis?	NO / YES	
19. Any injuries to the lower limb? (e.g. hip, knee, ankle)	NO / YES	
20. Serious illness (e.g. liver disease)?	NO / YES	
21. Neurological disorders?	NO / YES	
22. Anxiety?	NO / YES	
23. (Other) psychological difficulties?	NO / YES	

24. Medication: Please list the medication you are currently taking and any other medication that you have taken in the past year

Type of medication	Reason for consumption	Duration of consumption and Dose

25. Present Problems - Are you currently troubled by any of the following?

Concentration/ Attention problems	NO / YES	Nature:
Memory problems	NO / YES	Nature:
Difficulties finding words	NO / YES	Nature:

26. Physical Activity

How many times per week do you take part in physical activity (e.g., walking, gardening, household chores, dancing) or exercise? _______

Please list the types of physical activities that you partake in:

Activity	**Number of times per week**

APPENDIX D: GET ACTIVE QUESTIONNAIRE

CSEP | SCPE
THE GOLD STANDARD IN EXERCISE SCIENCE AND PERSONAL TRAINING

Get Active Questionnaire

CANADIAN SOCIETY FOR EXERCISE PHYSIOLOGY –
PHYSICAL ACTIVITY TRAINING FOR HEALTH (CSEP-PATH®)

Physical activity improves your physical and mental health. Even small amounts of physical activity are good, and more is better.

For almost everyone, the benefits of physical activity far outweigh any risks. For some individuals, specific advice from a Qualified Exercise Professional (QEP – has post-secondary education in exercise sciences and an advanced certification in the area – see csep.ca/certifications) or health care provider is advisable. **This questionnaire is intended for all ages – to help move you along the path to becoming more physically active.**

☐ I am completing this questionnaire for myself.

☐ I am completing this questionnaire for my child/dependent as parent/guardian.

PREPARE TO BECOME MORE ACTIVE

The following questions will help to ensure that you have a safe physical activity experience. Please answer **YES** or **NO** to each question before you become more physically active. If you are unsure about any question, answer **YES**.

YES	NO	
		1 Have you experienced **ANY** of the following (A to F) **within the past six months?**
○	○	**A** A diagnosis of/treatment for heart disease or stroke, or pain/discomfort/pressure in your chest during activities of daily living or during physical activity?
○	○	**B** A diagnosis of/treatment for high blood pressure (BP), or a resting BP of 160/90 mmHg or higher?
○	○	**C** Dizziness or lightheadedness during physical activity?
○	○	**D** Shortness of breath at rest?
○	○	**E** Loss of consciousness/fainting for any reason?
○	○	**F** Concussion?
○	○	**2** Do you currently have pain or swelling in any part of your body (such as from an injury, acute flare-up of arthritis, or back pain) that affects your ability to be physically active?
○	○	**3** Has a health care provider told you that you should avoid or modify certain types of physical activity?
○	○	**4** Do you have any other medical or physical condition (such as diabetes, cancer, osteoporosis, asthma, spinal cord injury) that may affect your ability to be physically active?

NO to all questions: go to Page 2 – ASSESS YOUR CURRENT PHYSICAL ACTIVITY

YES to any question: go to Reference Document – ADVICE ON WHAT TO DO IF YOU HAVE A YES RESPONSE

CSEP | SCPE Get Active Questionnaire

THE GOLD STANDARD IN EXERCISE SCIENCE AND PERSONAL TRAINING

ASSESS YOUR CURRENT PHYSICAL ACTIVITY

Answer the following questions to assess how active you are now.

1 During a typical week, on how many days do you do moderate- to vigorous-intensity aerobic physical activity (such as brisk walking, cycling or jogging)? DAYS/ WEEK

2 On days that you do at least moderate-intensity aerobic physical activity (e.g., brisk walking), for how many minutes do you do this activity? MINUTES/ DAY

For adults, please multiply your average number of days/week by the average number of minutes/day: MINUTES/ WEEK

Canadian Physical Activity Guidelines recommend that adults accumulate at least 150 minutes of moderate- to vigorous-intensity physical activity per week. For children and youth, at least 60 minutes daily is recommended. Strengthening muscles and bones at least two times per week for adults, and three times per week for children and youth, is also recommended (see csep.ca/guidelines).

GENERAL ADVICE FOR BECOMING MORE ACTIVE

Increase your physical activity gradually so that you have a positive experience. Build physical activities that you enjoy into your day (e.g., take a walk with a friend, ride your bike to school or work) and reduce your sedentary behaviour (e.g., prolonged sitting).

If you want to do **vigorous-intensity physical activity** (i.e., physical activity at an intensity that makes it hard to carry on a conversation), and you do not meet minimum physical activity recommendations noted above, consult a Qualified Exercise Professional (QEP) beforehand. This can help ensure that your physical activity is safe and suitable for your circumstances.

Physical activity is also an important part of a healthy pregnancy.

Delay becoming more active if you are not feeling well because of a temporary illness.

DECLARATION

To the best of my knowledge, all of the information I have supplied on this questionnaire is correct. If my health changes, I will complete this questionnaire again.

I answered NO to all questions on Page 1

Sign and date the Declaration below

I answered YES to any question on Page 1

Check the box below that applies to you:

- ☐ I have consulted a health care provider or Qualified Exercise Professional (QEP) who has recommended that I become more physically active.
- ☐ I am comfortable with becoming more physically active on my own without consulting a health care provider or QEP.

Name (+ Name of Parent/Guardian if applicable) [Please print] | Signature (or Signature of Parent/Guardian if applicable) | Date of Birth

Date | Email (optional) | Telephone (optional)

With planning and support you can enjoy the benefits of becoming more physically active. A QEP can help.

☐ Check this box if you would like to consult a QEP about becoming more physically active. (This completed questionnaire will help the QEP get to know you and understand your needs.)

APPENDIX E: FOOD LOG

24 Hour Food Log

Please fill out this food log as accurately as possible including all food, water, alcohol, and supplements taken starting 24 hours ago up until now. You will be required to match this food intake to the best of your ability when returning for the next two sessions. This log will be sent to you 24 hours before your next session to remind you what you ingested. On the day of participation, please do not drink coffee or other beverages containing caffeine.

Time	Food/Drink	Serving Size	Condiments/Notes
Ex. 10:00am	Oatmeal	1.5 cups	Honey, cinnamon

APPENDIX F: BORG SCALE (RPE)

BORG SCALE
Rating of Perceived Exertion

6	
7	**Very very light**
8	
9	**Very light**
10	
11	**Fairly light**
12	
13	**Somewhat hard**
14	
15	**Hard**
16	
17	**Vary hard**
18	
19	**Very very hard**
20	

APPENDIX G: Table 1. Characteristics of participants including age, sex, height, and shoulder width.

PARTICIPANT	AGE (years)	SEX	HEIGHT (cm)	SHOULDER WIDTH (cm)	WALKING SPEED (m/s)
1	22	M	172	55	1.5
2	24	F	168	42	1.45
3	21	F	178	42	1.2
4	23	F	167	41	1.43
5	28	F	155	43	1.5
6	24	F	180	45	1.28
7	23	M	180	42	1.35
8	23	F	175	44	1.45
9	23	F	170	42	1.59
10	23	M	167	53	1.6
11	24	M	182	42	1.25
12	23	M	185	53	1.6
13	24	M	190	50	1.36
14	22	F	177	42	1.5
15	21	F	165	43	1.58
16	23	M	172	48	1.65
17	25	M	183	45	1.33
18	28	M	170	49	1.24
19	21	F	165	39	1.5
20	26	M	157	46	1.75
21	24	F	154	41	1.6
22	24	F	165	43	1.3
23	20	F	157	42	1.3
24	23	M	175	50	1.25
25	23	F	177	43	1.35
26	21	F	187	43	1.3
27	25	F	173	46	1.32
28	23	M	155	46	1.45
29	23	M	166	52	1.4
30	23	M	175	49	1.2
31	23	F	167	39	1.24
32	22	F	182	43	1.1
33	20	F	193	38	1.4
34	23	M	157	44	1.38
35	24	F	185	40	1.25
36	24	F	172	44	1.5
Average	23.2		172.16	44.69	1.4
SD	1.79		10.35	4.26	0.15