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Peripheral Visual Motion Sensitivity in Previously Concussed, Asymptomatic Individuals

Alyssa Prangley
pran5160@mylaurier.ca

PERIPHERAL VISUAL MOTION SENSITIVITY IN PREVIOUSLY CONCUSSED, ASYMPTOMATIC INDIVIDUALS

By

Alyssa Prangley

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"There cannot be mental atrophy in any person who continues to observe, to remember what he observes, and to seek answers for his unceasing hows and whys about things."

-Alexander Graham Bell

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Glossary of Terms and Abbreviations

Term	**Definition**
ANOVA	**Analysis of variance**
AP	**Anterior-posterior**
CNS	**Central nervous system:** Part of the nervous system that includes the brain and spinal cord.
COM	**Center of mass:** A weighted average of the whole-body mass, such that the whole mass is equally distributed over the vertical projection of this point. For the purposes of the current study, COM is a weighted average of the trunk segment, wherein the coordinates of the left and right acromioclavicular joints are used to calculate a weighted average with a marker at the xiphoid process, to create a vertical projection of the individual's position in space.
CP	**Critical point:** A change in environment resulting in the limits of the action being reached and a transition phase into a different action
CVV	**Coefficient of variation of velocity**
HMD	**Head mounted display**
IRED	**Infrared light-emitting diodes**
ML	**Medial-Lateral**
NC	**Non-concussed:** Participants categorized as non-concussed control subjects
NDI	**Northern Digital Inc.**
PCA	**Previously concussed, asymptomatic:** Individuals having sustained a concussion a minimum of two weeks prior who are no longer experiencing concussion like symptoms
SD	**Standard deviation**
SR	**Shoulder rotation:** magnitude of rotation about the vertical axis, measured in degrees from the midline
SW	**Shoulder width:** measurement of each participants widest point in

centimeters, between glenohumeral joints

TOC **Time of crossing:** moment in time when the participant passes across the origin, located at the mid-point of the aperture

VR **Virtual Reality:** environment in which the experiment took place

Abstract

Background: Individuals acquire information about self-motion from the environment which specifies actions necessary to be successful (Fajen & Matthis, 2011). However, concussed individuals demonstrate residual disturbance in execution of postural movement at 30 days post injury, depicting an impaired ability to perceive self-motion in a visually conflicting environment (Slobounov et al. 2006). The objective of this thesis was to investigate the extent to which one's behaviours on a central field of view task are influenced by the amount and type of peripheral visual movement during a collision avoidance task, as well as to determine the additive effects of changes to balance control through the examination of the behaviours of a previously concussed population. The study utilized the closing doors of a virtual subway train to create an aperture for passage. For the purposes of this study, peripheral visual stimuli was a technique in which objects located within an individual's peripheral field of view were manipulated to be absent, stationary/relatively stationary (veridical optic flow), or move independent of the participant's movements (non-veridical optic flow). It was hypothesized that individuals would perform best when the environment provided visual information regarding one's own self motion. It was expected that a critical point (i.e., when the limits of action are reached and a transition phase into a different action occurs (Warren & Whang, 1987)) would emerge, which would be impacted by the different levels of peripheral visual environment, eliciting a change in critical point. Furthermore, it was anticipated that previously concussed asymptomatic individuals would elicit more variable behaviours (i.e., inconsistent path selection when aperture width remains constant) compared to non-concussed counterparts (Baker & Cinelli, 2014), as a product of the peripheral visual environment.

Methods: Previously concussed (3-12 months prior) asymptomatic young adults (N=12) were recruited, along with age and gender matched non-concussed controls (N=12). Participants walked along a 7m virtual path (via HTC Vive) towards a set of subway doors and were instructed to safely board the train without colliding with the doors. When the participants were 2m from the doors, they began to close at a constant rate such that the final door aperture width at the time of crossing ranged from 35-85cm (in 10cm increments). Participants performed aperture crossing trials during one of four peripheral environments: 1) ground plane only; 2) ground plane plus stationary poles in the peripheral environment; 3) ground plane with stationary humanoids in the peripheral environment; or 4) randomly moving humanoids. Participants were exposed to three trials of each aperture width within each environment for a total of 72 walking trials (6 widths x 4 conditions x 3 trials). Kinematic data was collected using a 3D motion capture system (Optotrak, NDI).

Results: The results revealed that participants executed significant shoulder rotations regardless of aperture width at time of crossing. It was found that non-concussed control subjects executed slightly larger shoulder rotations for smaller apertures (i.e., 35, 45, and 55cm) compared to the largest aperture ($p<.05$); a behaviour which was not seen within the previously concussed asymptomatic group. It was found that participants walked faster during the randomly moving humanoids condition compared to the other three peripheral visual environments regardless of aperture width and group ($p<.05$). The different environments had no effect on rotation magnitude ($p>.05$), coefficient of variation of velocity ($p>.05$), or medial-lateral stability during the approach phase ($p>.05$).

Conclusion: The findings of this study suggest that although a significant difference was found between aperture sizes for non-concussed controls, all individuals were found to employ a more conservative approach (i.e., "one solution fits all" strategy) to ensure success within each of the peripheral visual environments. As such, further research is required to assess the contributions of peripheral body information during an aperture crossing task and further the understanding of the behaviours demonstrated by each group. In addition, a more comprehensive sample of previously concussed asymptomatic individuals from various time points since concussion recovery will provide further insight into potential visuomotor deficits within this population.

CHAPTER I: Introduction

Visual Motor Control

Throughout daily life we are continually presented with cluttered environments, which require the integration of many sensory systems to navigate. Whether it is passing through a doorway, finding your way down a busy street, or boarding a train at the subway station; the visual, vestibular, and somatosensory systems provide information to assist in the control of locomotion and ensure collision avoidance. During locomotion, the visual system provides valuable information about self-motion, body position, position of body segments in relation to the environment and to one another, and the environment (Patla, 1998). The ability to perceive both self-motion as well as the motion of objects within the environment is essential to collision avoidance and safe navigation through the environment. The perception of self motion is used to detect potential hazards, decide a course of action, prepare for an action, initiate movement, and make appropriate adjustments to ensure the successful execution of the movement.

Two primary visual streams have been proposed to guide the transfer of visual information (Milner & Goodale, 1995). The dorsal stream primarily sends information regarding vision-for-action, influencing the production of motor behaviour without consciousness, while the ventral stream is more utilized for vision-for-perception, making conscious decisions for planning courses of action toward an overall goal (Tresilian, 2012). Vision is the predominate system used to gather information at a distance and allows for the coordination of whole body movements, through the collection of information about actions and positioning in order to maintain upright locomotion (Patla, 1998). The knowledge of the properties and layout of the environment is provided through one's visual system which in turn provides guidance of movements (Patla, 2004). This is completed through active gaze (i.e. the moving eye), which allows for visual data acquisition and effective locomotion (Cinelli, Patla, & Allard, 2009). Throughout the entirety of locomotion, visual control is present; from the establishment of body posture to allow the initiation of movement through the coordination of movements to produce rhythmic gait patterns, informing the individual about the body and its parts through feedback, and finally, in the termination of locomotion, visual control is the predominate source (Patla, 1997).

Movement is perceived through two systems, one which detects visual motion of the environment across the retina and another which detects movements of the eyes within the head (Snowden, Thompson, & Troscianko, 2006). According to Tresilian (2012), optic flow is defined as, "the continuous change over time of the spatial pattern of light reaching a point as it moves through its surroundings" (p.204). The main characteristic of optic flow is the motion of the changes in light intensity which parallel to the features within the environment. Retinal image flow is the continuous change of an image formed over time and is comprised of a translational component (projection of optic flow) and rotational component (flow due to the rotation of the eye). The translation portion of the image flow relies on both the motion of the eye through the environment as well as the distances of the visible points surrounding. This is used to tell how far images are from one another as points near to the eye move faster than those further away however it is difficult to use this in reference to oneself. The rotational component of image flow is the image motion, which is produced by an individual's eye movements (i.e. pursuit eye movements). Therefore, when the individual fixates on a stationary object while moving through the environment, the image flow is produced through the summation of the translational and rotational components (Tresilian, 2012). The perception that we are moving through the environment is derived from the image flow as it allows the formation of perception of self-motion. An environment which is rich in information allows the individual to control his or her movements (Warren, Kay, Zosh, Duchon, & Sahuc, 2001). However, cluttered environments with both stationary and moving obstacles create potential impediments to locomotion and can pose a challenge, particularly for individuals experiencing sensory motor deficits.

In a study conducted by Paulus, Straube, and Brandt (1984) assessing postural sway in young adults, it was noted that postural sway increased in the anterior-posterior direction when the participants were limited to foveal (i.e., central) vision compared to the full field of view baseline condition. In comparison, when limited to peripheral vision the increase in sway compared to baseline was minimal. Therefore, visual input from only the peripheral visual field provided feedback which assisted in the control of sway similar to that of the full field of view, while foveal visual feedback provided minimal control over postural stability (Paulus, Straube, & Brandt, 1984).

Perception Action Integration

Perception is the process of obtaining information about one's surroundings and one's body from the stimulation of sensory systems making this information available for a variety of tasks such as decision making, reasoning, memorizing, communicating, and the planning and controlling of motor actions (Tresilian, 2012). Visual attention refers to the cognitive operations which filter information from a visual scene to select between relevant and irrelevant information (McMains & Kastner, 2009). Visual attention is comprised of both simple and complex demands. The use of perception-action coupling to control one's behaviours requires the individual to have proper perceptual information to allow for the regulation of actions (Cinelli et al., 2009). Complex visual attention challenges one's ability to accurately attend to and discriminate between multiple different stimuli which are competing as they are presented simultaneously. As the complexity of the stimuli increases, individuals experience a reduced processing speed universally across the sensory systems and thus require more time to complete the task at hand (Suchoff, Ciuffreda, & Kapoor, 2001). An example of such a task is walking through sliding doors. Individuals are likely to adopt a similar strategy to that of navigating a static aperture, by steering towards the area of the gap which afforded the greatest success (Cinelli, Patla, & Allard, 2008; Cinelli et al., 2009). Visual fixations towards the goal, in this case the gap between two doors, assist the individual in correctly aligning oneself to safely pass through the doors, while the peripheral visual field assists in calculating the variability in the movement of the doors and guiding the individual through the aperture relying on optic flow (Cinelli et al., 2009). Unfortunately, individuals who have visual perceptual disorders experience a reduced ability to navigate through dynamically changing environments, such as this, safely. For instance, Aravind, Darekar, Fung, & Lamontagne (2015) examined the performance of individuals with visuospatial neglect during a virtual reality-based obstacle avoidance navigation task. Participants depicted a delayed ability to detect approaching obstacles in the both the head-on and contralesional directions, leading to obstacle collision even when the individual retained adequate locomotor abilities. It was concluded that visuospatial neglect leads to an altered perception of obstacles within an environment and subsequent difficulty with obstacle avoidance (Aravind et al., 2015).

Sensory Contributions to Perception

The process of completing corrective postural adjustments requires the individual to determine the timing, direction, and degree of modification required through the compilation of information from the visual, vestibular, and somatosensory system inputs (Nashner, 1982). Through sensory organization, the feedback from each individual sense is weighted based on the context of the task and is used to control one's balance. This is a complex process which requires the central nervous system to determine the most appropriate combination of sensory feedback from the three systems within a particular context to allow for the maintenance of postural stability (Nashner, 1982; Patla, 1997; Winter, 1995; Woollacott, Shumway-Cook, & Nashner, 1986).

Each sensory system plays a specific role in balance control. The visual system is utilized as a form of proactive control, allowing an individual to identify the most efficient path for locomotion through an environment (Cinelli & Patla, 2007; Hackney & Cinelli, 2011; Patla, 1997). This is achieved through the identification of information about the static and dynamic aspects of the environment at a distance (Patla, 1997). In contrast, the somatosensory system gathers proprioceptive information from the lower limbs in regards to the location of the limb within the environment and in relation to the other limbs. Furthermore, sensory receptors located within the soles of the feet detect changes in pressure, providing valuable information regarding the distribution of weight upon the support surface (Shumway-Cook & Horak, 1986; Woollacott et al., 1986). The vestibular system provides information regarding the position and movement of the head with respect to gravity and inertial forces. This is of great importance in updating one's sense of position in space through detection of linear and angular acceleration changes of the head (Shumway-Cook & Horak, 1986; Tresilian, 2012). The information gathered from each of these sensory systems appears to be redundant, as minimal increases in sway are noted when eyes are closed and many individuals are capable of independent stance and gait despite a loss of somatosensory, vestibular, or visual function. However, it has been previously observed that under a variety of situations the maintenance of optimal balance control requires the integration of information from each of the sensory systems (Horak, Nashner, & Diener, 1990). Patients with vestibular deficits are an example of this, as they may demonstrate difficulty balancing on one leg, holding a heel-to-toe stance, and abnormal head and body righting reactions following a perturbation as a result of an inability to couple vestibular information with visual and somatosensory system inputs (Horak et al., 1990).

Locomotion

Postural control involves controlling the body's position in space for orientation and stability (i.e., ability to maintain balance). The requirements for postural control are dependent upon the task as well as the environment. Each task encountered has an orientation and stability component with demands changing between tasks. For instance, walking across ice may result in the decrease of one's stability (i.e., extreme widening of one's base of support) to maintain postural orientation (i.e., avoid falling and remain upright). Stability is a fundamental component of controlling one's body in an upright position safely while adapting to the dynamic nature of the environment.

During locomotion, postural control becomes unstable as an individual moves their centre of mass (the weighted average of the central point of an individual's total body mass, COM) outside of their base of support (the area of the body which is in contact with ground or support surface, BOS) with each stride (Magee, 2007; Winter, 1995) to allow forward propulsion of the body in a continuous motion. This establishes an unstable situation as the COM moves ahead of the BOS and leads to a series of compensatory steps to allow for an increase in the dynamic BOS in hopes of regaining control of the dynamic COM and one's stability. One's dynamic balance is established as the swing limb follows a trajectory that will ensure balanced conditions during the next stance phase of the gait cycle (Winter, 1995). This dynamic relationship between the COM and BOS during locomotion results in the body moving in a controlled manner through on-line control, requiring feedback from each step to achieve stability in the next.

Walking provides a variety of internal and external perturbations that an individual must accommodate for to advance successfully, such as obstacle avoidance, anticipatory postural adjustments, navigating surfaces, and path selection towards a goal. To successfully complete a step, adjustments and modifications to an individual's behaviour must be made. The adjustments are made based on the information provided from the sensory systems and are critical to maintaining dynamic postural stability (Patla, 1997; Winter, 1995; Woollacott et al., 1986).

Aperture Crossing

Per Warren & Whang (1987), the affordances of a situation or object are the specific opportunities it provides an individual for action, which can be body- or action-scaled. When examining apertures within an environment, passage is body-scaled and afforded if the width of the aperture is greater than that of the individual's narrowest horizontal dimension, the shoulders. With aperture widths that are narrower than the individual's shoulders, the individual must rotate his or her body to allow for a certain margin of safety for body sway and potential error. Action-scaled affordances are dependent on one's movement capabilities and the selection of the appropriate actions for the task. For instance, passage of a shrinking aperture (i.e., closing subway car doors) is action-scaled and afford if the individual has the means to increase gait speed to a rate faster than the rate at which the aperture is shrinking.

A recent study by Fajen & Matthis (2011) explored the way individuals perceive affordances based on action-scaled information of their locomotor capabilities. This requires additional body-scaled information when looking at the context of the ability of an individual to perceive whether a shrinking gap between two converging obstacles is passable. Within the experiment, optic flow rates were manipulated relative to the rate of walking to provide optic flow at a rate 0.5 times or 0.8 times veridical, thus impacting one's perception of movement. The individual acquires information about self-motion from the environment which specifies his or her perceived minimum speed which is intrinsic to the person (i.e., eye height relative to shoulder width) and depicts the amount of time remaining before the gap closes relative to one's self. This allows the individual to have a direct perception about whether a shrinking gap is passable or not.

It was determined, through the testing of multiple aperture sizes, that critical points emerge when the limits of the action are reached and a transition phase into a different action, such as a shoulder rotation, occurs (Warren & Whang, 1987). Young adults tend to have a critical point of 1.3 times his or her shoulder width (SW) at which point any aperture smaller will induce a reduction of one's medial/lateral width through a shoulder rotation to ensure safety of passage (Hackney & Cinelli, 2011; Warren & Whang, 1987). Overall, it has been determined that an individual perceives the affordance of passage of an aperture which then dictates which actions are possible with respect to the aperture.

Potential avoidance actions range from maintaining frontal walking gait, reorganizing the musculature to allow for shoulder rotation, or choosing an alternate route around the aperture (i.e., circumvention). Apertures which are perceived to be narrower than the smallest horizontal body dimension do not afford passage to the individual, leading to a change of action to avoid collision. A previous study found that the decision to make a change in action, as depicted by the critical point, was more variable in individuals who had previously sustained a concussion and were cleared for return to play compared to non-concussed individuals. This highly variable nature was noted with apertures 0.8-1.4x the individual's SW (Baker & Cinelli, 2014) in contrast to healthy young adults who tend to be accurate and consistent in their dynamic stability and action strategies (Warren & Whang, 1987). In addition, the previously concussed participants demonstrated less cautious behaviour in comparison to controls as they tended to pass through apertures which were only 1.0x his or her SW or greater rather than deviate around the obstacle, while controls did not begin consistently walk through apertures until the gap was 1.4x SW or greater (Baker & Cinelli, 2014). It is still unclear as to why previously concussed individuals act less cautiously than age-matched non-concussed young adults however, the results still suggest that previously concussed individuals have less consistent action strategies compared to their counterparts.

Deficits within concussed populations

Through the examination of the contributions of the sensory systems within special populations, such as older adults or those suffering from pathologies, we can begin to gain an understanding as to the importance of non-visual systems (i.e. sensory and/or vestibular) in visually guided movements. Individuals who have sustained a concussion appear to have significant deficits within the vestibular system, as depicted through balance deficits (Powers, Kalmar, & Cinelli, 2014b). Changes to one's sensory information leads to changes in balance control and can cause changes to visuomotor processing (i.e., perception-action integration) (Hackney & Cinelli, 2012).

A concussion is defined as a transient disturbance of one's brain function as a result of a traumatic event which involves a complex pathophysiological process (McCrory et al., 2013). Further to this, the definition of sport-related concussion has been defined as a traumatic brain injury which is induced by biomechanical forces. As of 2012, an estimated 3.8 million concussions are sustained in the United States per year during recreational activity and competitive sport (Harmon et al., 2013). The 2017 Consensus statement on Concussion in Sport reported that for majority of concussed athletes, the first two weeks following injury will include rapid improvements in cognitive deficits, balance, and symptom presentation. However, it was determined that a minority of cases take beyond 10 days to experience clinical recovery. Beyond clinical recovery, it was determined that the physiological time of recovery for a concussion may outlast the time for resolution of symptoms (Mccrory et al., 2017). Individuals who have previously sustained a concussion and appear relatively "normal" may still be experiencing significant deficits. These deficits could manifest in attention, concentration, ability to integrate sensory information, motor performance, and higher level intellectual tasks. There is a potential for these deficits to be reflected in an inability to suppress one's awareness of background stimuli while attending to a specific task, thus success at any given activity may require the individual to have optimal environmental surroundings to perform the activity (Suchoff et al., 2001).

Previous research (Alsalaheen et al., 2010; Geurts, Knoop, & Van Limbeek, 1999; Geurts, Ribbers, Knoop, & Van Limbeek, 1996; Powers, Kalmar, & Cinelli, 2014a; Powers et al., 2014b) indicates that many concussed individuals suffer from persistent balance deficits beyond the standard recovery period previously outlined by McCrory et al. in the 2017 Consensus Statement. This is demonstrated by an increased velocity of centre of pressure (vCOP) during quiet stance, despite the individual experiencing a reduction of symptoms and standard testing procedures (BESS test) detecting no marked deficits (Powers et al., 2014b). The integration of information obtained from the vestibular and somatosensory systems by the vestibular cerebellum is imperative to the maintenance of balance and postural control, especially in the absence of correct visual information (Cullen, 2012). The primary pathway for the transmission of signals from the otolith organs, which detect linear acceleration, to the extensor musculature of the lower limb is the lateral vestibulospinal tract. The vestibulospinal reflexes produce corrective adjustments to preserve one's upright posture (Cullen, 2012; Khan & Chang, 2013). This reflex allows for the extensors to be activated to counteract the force of gravity upon the body and help the individual to remain upright (Highstein & Holstein, 2012; Khan & Chang, 2013). Additionally, the left and right ankle extensors work in collaboration to maintain balance control in the anterior posterior direction (Winter, 1995). It has been suggested that an individual may experience impairments to the lateral vestibulospinal tract following a concussion and demonstrate balance control deficits in the anterior-posterior direction due to damage to the aforementioned pathways. This impairment presents as an increase in the compensatory torques about the ankle during static balance (Powers et al., 2014b).

Under dynamic balance conditions, individuals with concussions are noted to have adopted a more conservative gait strategy to allow for the maintenance of dynamic stability through a shortened stride length and thus a reduction in one's anterior-posterior velocity (Catena, van Donkelaar, & Chou, 2007; Parker, Osternig, van Donkelaar, & Chou, 2005). However, in a study by Powers and colleagues (2014a), no differences were found between the concussed individuals and healthy controls in the minimum dynamic stability margin during a steering task, despite inconsistencies in segmental re-orientation. Individuals within the concussion group were found to have variable segmental re-orientation techniques, fluctuating between 1) head re-orientation preceding trunk re-orientation, 2) trunk re-orientation first onset, and 3) a simultaneous rotation of the head and trunk segments throughout the task (Powers et al., 2014a).

Individuals with concussions rely heavily upon vision to control balance (Geurts et al., 1999) despite a variety of comorbid visual deficits (Brahm et al., 2009; Doble, Feinberg, Rosner, & Rosner, 2010). In a study by Slobounov, Slobounov, & Newell (2006), ten individuals who had sustained a concussion following baseline testing were tested 3, 10, and 30 days post injury using virtual reality graphics for assessment of concussion. Participants stood for thirty seconds at a time while viewing a visual scene of a "moving room" (adapted from the original studies conducted by David Lee and colleagues) under three different rates of room movement. It was determined that even at thirty days post injury, participants were still displaying postural instability as depicted by an inability to produce coherent oscillatory postural movement similar to that of the virtual room, in comparison to their baseline values (Slobounov, Slobounov, & Newell, 2006). Further investigation into the role of vision and the effects of peripheral visual motion during a collision avoidance task within dynamic balance control conditions will assist in understanding how stability may be impacted during a complex task.

Conclusion and Rationale

According to Suchoff, Ciuffreda, & Kapoor (2001), testing an individual's functional abilities within a controlled environment under favourable conditions may not give an accurate depiction as to the actual abilities of the individual in more applicable settings (i.e., athletic playing field). It is known that individuals demonstrate an increase in AP sway when limited to central vision, with no change in sway when limited to peripheral vision. However, this was found during quiet stance. Therefore, it is imperative to first identify dynamic situations in which potential deficits can be identified and from there the appropriate testing can be developed. Through the examination of the contributions of the sensory systems within a previously concussed, asymptomatic population, we can begin to gain an understanding of the importance of non-visual systems in visually guiding movements.

Research Objectives

The objective of the current study is two-fold: 1) to investigate the extent to which one's behaviours on a central field of view collision avoidance task are influenced by the amount of peripheral movement in virtual reality; and 2) to determine whether recently concussed asymptomatic (PCA) individuals behave differently than non-concussed (NC) individuals.

Hypotheses

I. All participants will demonstrate a significant change in action (i.e., increased shoulder rotation) as aperture widths decrease below 1.3x participant's shoulder width (critical point). In addition, critical point values will vary within groups depending on the peripheral visual environment presented, such that greater critical point values will be observed as peripheral visual stimuli becomes more complex.

II. Critical point values will differ between groups, with previously concussed, asymptomatic (PCA) individuals displaying variable (within and between) critical points, similar to previous findings. Baker & Cinelli (2014) found previously concussed individuals to display greater critical point variability when compared to young adults.

III. Participants will maintain a constant onset of rotation relative to the onset of door movement, which will lead to an increase in rate of rotation for smaller aperture widths to facilitate the modulation of SR to the aperture size presented.

IV. Participants will display an increase in approach speed from Phase 1 (Empty and Poles) to Phase 2 (Avatar and Movement), as the inclusion of avatars will lead to a more immersive setting and an increase sense of urgency to reach the goal.

V. PCA group will display a greater difference in velocity between the Approach and Crossing phase due to requiring more time to decide the correction action to pass through a given aperture in VR environments with greater perceptual challenge (i.e., Phase 2 conditions).

VI. Groups will perform differently depending on the peripheral visual environment presented, with both groups having the greatest (most accurate) performance within the stationary peripheral visual stimuli condition as it will provide an environment which is rich in visual information (Warren et al., 2001).

VII. PCA group will be more affected by the peripheral visual stimuli compared to the NC, leading to poor dynamic stability in the form of increase ML COM variability during straight forward walking and increase variability in approach speed. Similar to findings using a visually conflicting scene during quiet standing, which found previously concussed individuals had poor posture stability thirty days post injury when compared to their pre-injury baseline (Slobounov et al., 2006).

CHAPTER 2: General Methodology

Participants

Participants were categorized into one of two groups (Table 1): 1) young adults between the ages of 18 and 30 years (non-concussed, NC) and; 2) young adults between the ages of 18 and 30 years who had sustained a concussion within the past 12 months and were no longer experiencing symptoms (previously concussed asymptomatic, PCA). PCA individuals were required to be asymptomatic for a minimum of two weeks prior to testing and no longer seeking treatment from a healthcare professional for his/her concussion; excluding individuals with concussions sustained following a motor vehicle accident to minimize the occurrence of comorbid injuries. Twelve prospective participants met the inclusion criteria for the PCA population. The individuals in the NC group were age and gender-matched to the PCA group and had no history of previous concussion in the past three years. Participants were excluded from the study if: 1) they had any known neurological impairment including but not limited to learning disability, other brain related conditions (excluding concussion within the PCA group); 2) physical limitations hindering limb movement which affected the individual's ability to walk at a comfortable pace along the 6m path for the duration of the study; 3) found to have vision less than 20/40 (0.3 logMAR) in either eye during visual tests; 4) found to have depth perception less than 70 sec of arc at 16 inches; 5) previous history of sensitivity to motion and/or virtual reality/3-Dimensional movies; 6) or any illness or disorder which may interfere with balance, decision making skills, and/or an individual's overall ability to complete 60 minutes of walking at a comfortable pace within a virtual reality setting. There was no significant difference between groups in demographic variables and baseline characteristics (p>0.05) aside from the average number of concussions over one's lifetime (p=0.0001).

Table 1: An overview of the demographic information for non-concussed and previously concussed, asymptomatic participants (Mean ± standard deviation).

	Non-Concussed (NC)	Previously Concussed (PCA)	P values
Gender	Male n=4 Female n=8	Male n=4 Female n=8	-
Average Age	21.67±2.84	21.67±2.99	p=1.000
Height (cm)	171.08±6.76	170.92±9.65	p=0.963
Weight (kg)	70.94±17.59	73.75±17.85	p=0.714
Shoulder Width (cm)	43.96±1.48	45.50±1.43	p=0.398
Visual acuity (logMAR)	L= 0.08±0.17 R= 0.13±0.30	L= 0.03±0.16 R= 0.04±0.14	(L) p=0.475 (R) p=0.358
Stereopsis test (sec of arc)	27.08±6.91	29.58±6.91	p=0.366
Average number of concussions over lifetime	0.20	1.67	p=0.0001
Time since Concussion	>4 years n=2 N/A n=10	<6mon n=7 >6mon n=5	-
Number of SCAT 3 symptom at time of testing	1.75±2.14	4.42±5.84	p=0.160
Severity of SCAT 3 symptoms at time of testing	2.67±3.85	8.67±13.28	p=0.157

Protocol

All participants completed three questionnaires prior to testing to provide general insight into the health and tendencies of the individual: 1) Risk Taking Behaviors Questionnaire to evaluate behavioral intentions of the individual or the likelihood the individual might engage in behaviors/activities deemed to be risky (refer to Appendix A); 2) General Health History questionnaire for demographic purposes and to gain insight into the health and wellbeing of the individual as well as activity level (Appendix B); and 3) Concussion Health History

Questionnaire to gain an understanding of any athletic involvement, concussion history, and symptomology (Appendix C). Within the Concussion Health History Questionnaire, participants completed the SCAT3 symptom and severity questionnaire to determine the symptomology of all participants at the time of testing. All questionnaires were completed after the individual gave their written and informed consent (Appendix D) in accordance with the Wilfrid Laurier University Research Ethics Board. The Wilfrid Laurier University Research Ethics Board approved all testing procedures.

In addition to the questionnaires, participants completed two visual tests to ensure compatibility with the Virtual Reality environment (VR). A stereopsis test was performed to determine sufficient depth perception (70 sec of arc at 16 inches or better) and a visual acuity test was performed to ensure participants had 20/40 vision or better in each eye. These tests were used as a screening tool to help ensure that participants had adequate vision for the VR task and help to minimize the inclusion of individuals who may have experienced adverse effects from participating in the study.

Experimental Design

This experiment was conducted within the Lifespan PsychoMotor Behaviour (LPMB) laboratory at Wilfrid Laurier University. Kinematic data was collected using five OptoTrak cameras bank (Northern Digital Inc., Waterloo, ON, Canada) sampling at a frequency of 100Hz. Each participant was outfitted with a front facing marker set-up to track the movements of the torso in space and time. Participants were outfitted with Infrared Emitting Diodes (IREDs) located on the xiphoid using a single rigid body, containing three IREDs and an additional five IREDs placed on the torso (two markers on the left and right acromioclavicular joints and one on the sternum) (Figure 1). The rigid body was secured to a chest mount and positioned at the xiphoid process. This marker set-up was used because both the Optotrack system and the HTC Vive (see below) communicated with their hardware via infrared light and on any trial the HTC Vive would produce noise on to one or more IREDS. So, to increase the chances of being able to calculate a weighted Centre of Mass calculation in time and space using torso markers from the xyphoid and shoulders as well as trunk angular rotations, extra (backup) markers were place on the body part of interest.

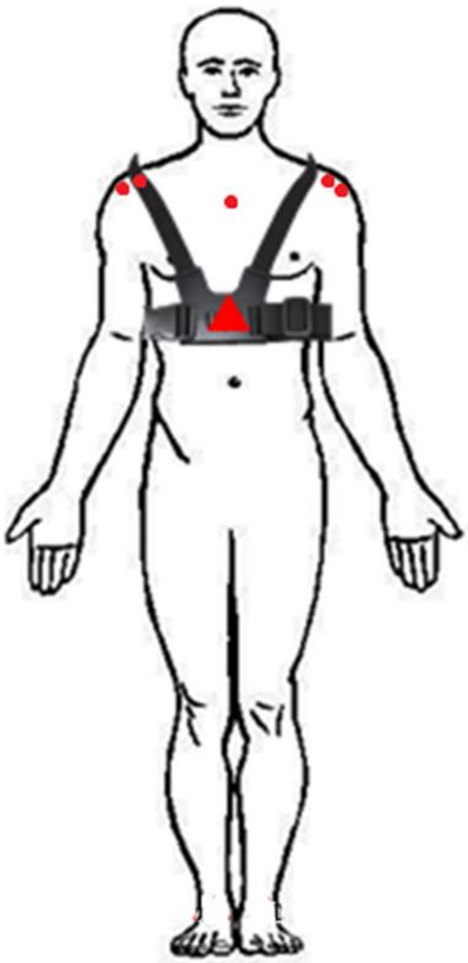

Figure 1: Configuration of rigid body (triangle) and markers (circles) used to represent the body in space during the collection of kinematic data.

Additionally, participants were outfitted with a HTC Vive virtual head mounted display (HMD) unit to provide the VR environment for the walking task and noise cancelling headphones were worn to provide scenario relevant ambient noise.

The experiment was conducted within a 10m by 6m space, with the start position located 6m from the subway aperture crossing (Figure 2). Prior to the onset of experimental trials, participants were given the opportunity to explore the VR environment in which the study took place for a more immersive experience. This allowed participants to walk within the VR to become familiar with one's perception of movement and walking speed. The VR environment consisted of a subway platform with a stationary train stopped with the doors open.

Participants were instructed to approach the train and pass safely through the doors and board the train without colliding with the doors.

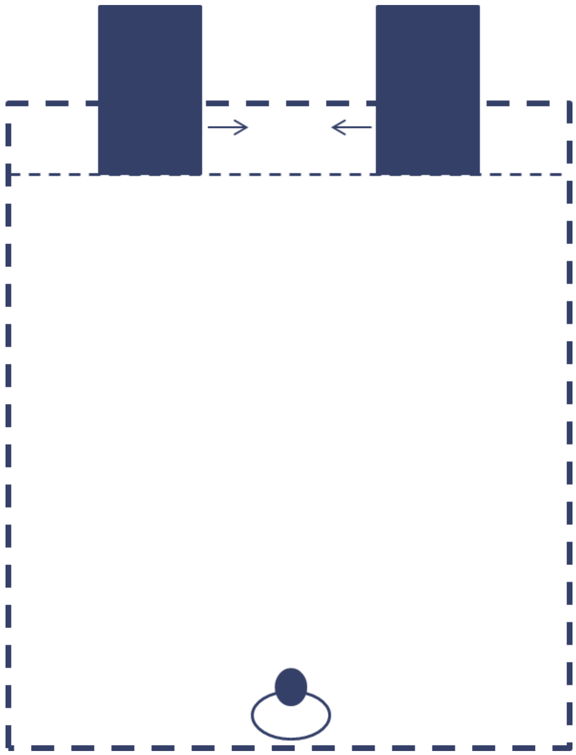

Figure 2: Simple illustration of experimental setup with participant approaching open doors of the subway train. The open aperture was located 6m from the start position, and set to 115cm to start. Doors began relative to participant's distance from the apertures resulting in one of six final aperture widths at time of crossing.

The doors had a constant rate of closure to 1 of 6 final aperture widths (ranging from 35 to 85cm, in 10cm increments) at the time of participant crossing. In order to achieve the final door aperture widths, the onset of closure was varied between participants based on the average approach speed for each participant. Trials were completed in four different peripheral visual stimuli environments, to add increasing complexity to the central field of view task (Figures 3 - 5).

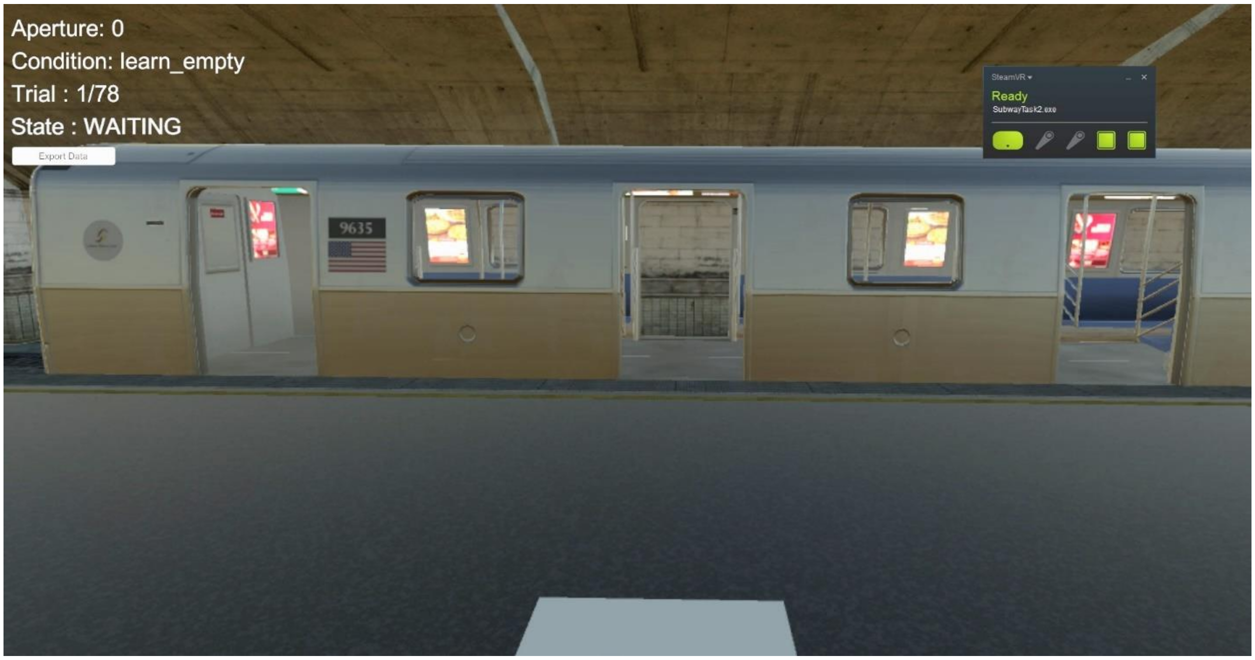

Figure 3: Virtual reality environment "Empty" from the view point of a participant while standing at the start position (white box).

Figure 4: Virtual reality environment "Poles" from the view point of a participant while standing at the start position (white box).

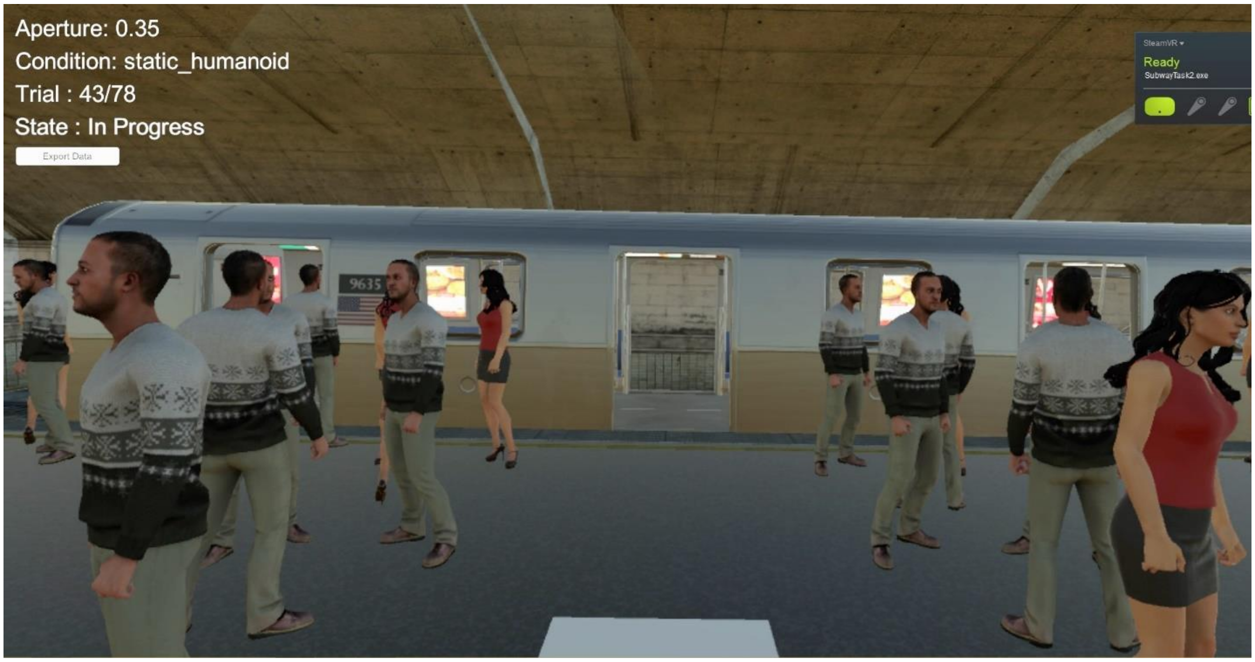

Figure 5: Virtual reality environment "Avatars" from the view point of a participant while standing at the start position (white box). The same configuration was utilized for the virtual reality environment "Movement".

Peripheral visual stimuli, for the purposes of this study, was a technique in which objects located within a participant's peripheral field of view were manipulated to be: 1) absent (Empty); 2) stationary/relatively stationary (Poles or Avatar, veridical optic flow); or 3) move independent of the participant's movements (Movement, non-veridical optic flow). The experiment was completed in two phases, each starting with three learning trials (Learners) used to orient the participant to the space and determine average walking speed (Table 2). Participants were required to complete the Phase 1 with no adverse effects prior to starting the Phase 2.

Table 2: Protocol for the completion of the experiment under two phases and four different peripheral visual environments.

Phase 1			Phase 2		
Learners	Empty	Poles	Learners	Avatar	Movement
Ground plane and train, no additional visual peripheral stimuli	Ground plane and train, no additional visual peripheral stimuli	Ground plane and train, addition of stationary poles	Ground plane and train, addition of stationary avatars	Ground plane and train, addition of stationary avatars	Ground plane and train, addition of avatars with random movement patterns

Phase 1 consisted of a randomization of 1) no additional peripheral visual stimuli (ground plane and train, Empty); and 2) stationary poles located in the participants peripheral field of view (Poles). Phase 2 consisted of a randomization of 1) stationary avatars (Avatar); and 2) moving avatars (Movement). The stationary peripheral visual stimuli consisted of poles (stationary) and avatars (relatively stationary with human-like sway characteristics) within the space but not obstructing the path of the participant to the doors in any way. Avatars were positioned in groups of three at the same coordinate location as the poles in the Poles condition. The moving peripheral visual stimuli (Movement) had the same avatar configuration as the Avatar condition but with the addition of the avatars completing random locomotion patterns without obstructing the path of the participant. Avatars moved at a rate of 1.2m/s; a rate selected based on average participant walking speeds during pilot testing. During Phase 2, avatars were also positioned inside the train to mimic a realistic scenario. Participants were exposed to three trials of each final aperture width (i.e., 3 trials x 6 final apertures= 18 trials per peripheral environment), presented in random order within each phase, for a total of 78 walking trials.

Data Analyses

Any missing kinematic data points were corrected using a cubic spline interpolation. The data was low pass filtered using a zero lag 4th order Butterworth filter with 3Hz cut-off frequency. The centre of mass (COM) for each participant was estimated using a weighted average calculation of the participants' torso in the Anterior-Posterior (AP) and Medial-Lateral (ML) directions over time (i.e. 25% allocated each to the left and right acromioclavicular joints and the remaining 50% allocated to the xiphoid), similar to that utilized by Winter, Patla, Prince, Ishac, & Gielo-Perezak (1998). These COM estimates allowed for the calculation of the average COM position, walking speed, ML COM position at time of crossing, and variability in velocity during the approach.

Equation 1:

$$COM(i) = 0.25 * (Left\ Shoulder(i)) + 0.25 * (Right\ Shoulder(i)) + 0.5 * (Trunk(i))$$

Shoulder Rotation

Shoulder rotation angle about the vertical axis (yaw) was calculated using the IREDs located on the left and right acromioclavicular joints. Each participant's starting angle about the vertical axis was calculated prior to participant's initiation of forward progression. This angle was then calculated for each frame, subtracting out the starting angle to determine degree of rotation. The average and standard deviation of rotation was calculated during the approach (start position to 1m prior to origin) for each aperture width, under each VR environment. The time of crossing was a specific point at which the participants were physically passing through the aperture to board the subway train. This data was identified by the participants' kinematics at the origin (i.e., subway train aperture). Shoulder rotation magnitude was said to have occurred if the angle of rotation about the vertical axis (Yaw) was ±3 standard deviations from the mean of start position angle. This measure was used to determine if participants were modulating their behaviour to the aperture width.

Equation 2:

$$TrunkYaw(i) = \operatorname{atan}\big(\big(RSh_{AP}(i) - LSh_{AP}(i)\big)/\big(RSh_{ML}(i) - LSh_{ML}(i)\big)\big)$$

where: LSh is the left shoulder

RSh is the right shoulder

AP is anterior-posterior position

ML is medial-lateral position

The rate of shoulder rotation was used to determine if participants were controlling their movements to achieve consistent SRs at time of crossing or modulate SRs to aperture size. This was calculated by dividing the magnitude of SR at time of crossing (degrees) by the onset of rotation (s). The onset of shoulder rotation was detected when the angle of rotation about the vertical axis (Yaw) was ±3 standard deviations of the start position angle and remained outside for more than 0.1s and was used to determine when the decision to rotate occurred. The rate of rotation accounts for the onset of rotation as well as the magnitude of rotation to give an overall representation of the individual's behaviour.

Speed (instantaneous calculation)

The instantaneous velocity of the COM was calculated as the change in displacement over a change in time beginning from the initiation of forward progression to the moment of aperture crossing.

Equation 3:

$$Velx(i)cm/s = \frac{(COMx(i+1)cm - COMx(i-1)cm)}{\left(\frac{frame(i+1) - frame(i-1)}{collection\ frequency\ (Hz)}\right)}$$

Walking speed for each trial was divided into two phases: 1) the Approach (start of movement to 2m prior to aperture crossing); and 2) Crossing (0.5m prior to the Time of Crossing) (Figure 6).

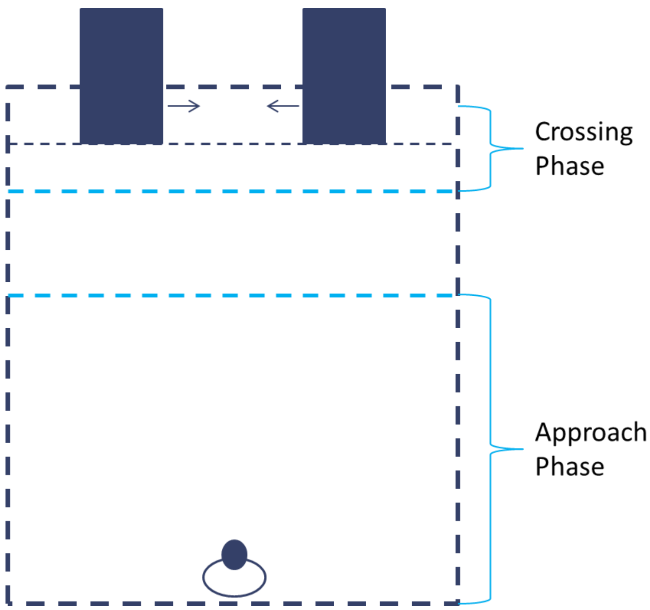

Figure 6: The Crossing Phase included 50cm prior to aperture to immediately after the aperture, while the Approach Phase include the start position to 2m prior to the aperture.

In order to determine if there was a change in walking speed between the Approach and the Crossing phases (i.e., reflection of decision making behaviour), the difference between them was calculated. The coefficient of variation of velocity (CVV= SD/average speed) was also calculated during the Approach phase. CVV was used to provide a representation of the variability of approach velocity within a trial. Any increase in variability across the conditions may be indicative of the influence of the increased peripheral visual motion across trials due to a reduced ability to maintain the rate of one's self motion.

Medial-lateral centre of mass variability

ML COM variability (standard deviation) was calculated during the Approach phase as a means to understand individuals' balance and dynamic stability within each trial across the conditions. Increases in variability of one's ML COM during straightforward walking along a flat surface are indicative of a reduction of one's ability to maintain balance control and dynamic stability. The standard deviation of the ML component of COM was calculated from the start position to aperture crossing (i.e., trigger).

Statistical Analyses

IBM SPSS Statistics software was used to run statistical analyses. Mixed-model repeated measures analysis of variance (ANOVAs) (between factor: groups (2); within factor: aperture size (6) and virtual reality environment (4)) were conducted comparing: magnitude of SR at time of crossing, SD of magnitude of SR at time of crossing, rate of rotation, average speed during the Approach, CVV, and difference in velocity from Approach to Crossing. For all ANOVAs with statistical significance, the Bonferroni post hoc test was used to make pairwise comparisons and determine which means differed.

Concussion health history questionnaire

Using data obtained from the concussion history questionnaire, a Pearson's correlation was used to determine if time since recovery of concussion as related to SD of SR at time of crossing in the PCA group. This was done to determine whether variability in rotation behaviours change with increased time since recovery of concussion. Baker & Cinelli (2011) found that previously concussed athletes depicted less consistent action strategies than non-concussed aged matched controls, resulting in an increased variability within individuals for aperture widths 0.8-1.4x their SW (i.e., apertures near one's critical point). For the purposes of this analysis, a theoretical critical point was selected for each participant based on previous research which determined that at 1.3 times an individual's SW, a critical point will emerge in which an individual's behaviour will change (Hackney & Cinelli, 2011; Warren & Whang, 1987). The theoretical width was then compared to the predetermined aperture widths of the VR and the nearest width was selected for analysis.

CHAPTER III: Results

Shoulder Rotation (SR, degrees)

It was hypothesized that individuals would demonstrate a change in action (i.e., shoulder rotations) as the subway doors began to move and aperture widths decreased in size, whereby participants would employ actions appropriately tuned to the aperture width at time of crossing. Furthermore, it was expected that PCA group would elicit different aperture crossing behaviours compared to NC group. To assess this, the SR angle magnitude at time of crossing was calculated. The results revealed a main effect of aperture width (F=3.191, p=0.010, n^2 =0.127, β=0.789) with an interaction between group and aperture width (F=4.173, p=0.002, n^2 =0.159, β=0.896). Post hoc tests using the Bonferroni correction revealed a decrease in SR magnitude while crossing the 85cm aperture when compared to SR magnitudes at 35cm, 45cm, and 55cm apertures (p=0.028, p=0.005, and p=0.047 respectively), in addition, SR magnitudes where smaller at 65cm when compared to 35cm and 45cm (p=.026 and p=0.008) (Figure 7). It was determined that SR for 55cm apertures, compared to 85cm apertures, were greater for NC than PCA (F=4.626, p=0.043). This aperture was determined to be at approximately 1.45x SW (65cm aperture divided by the SW of each participant, averaged across all participants). No significant effects were found for VR environment (F=0.674, p=0.571, n^2=0.030, β=0.185), group (F=0.047, p=0.831, n^2 =0.002, β=0.055), or between group and VR environment (F=2.366, p=0.576, n^2 =0.026, β=0.163).

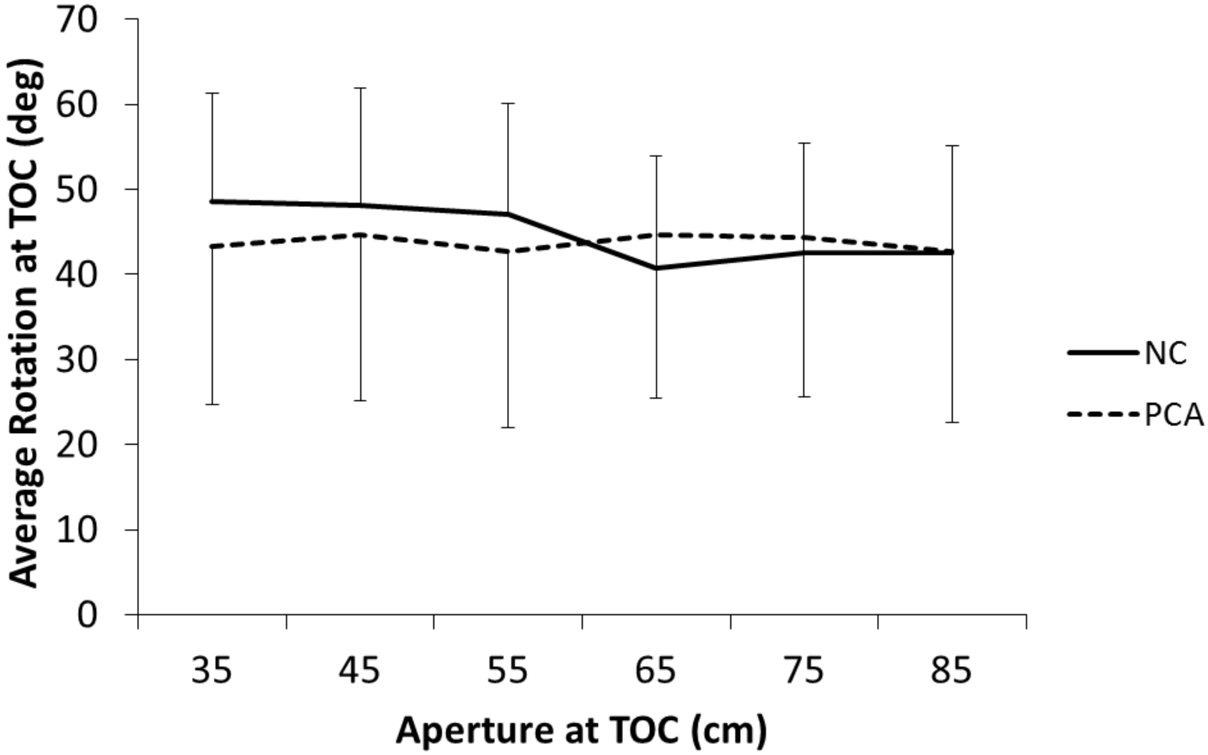

Figure 7: Average rotation angle at time of crossing, in degrees, collapsed across VR peripheral environments represented by group (solid black representing Non-concussed, dashed representing Previously concussed, asymptomatic). Significant differences were found in magnitude of rotation when comparing 85cm width to 35cm, 45cm, and 55cm apertures ($p<0.05$), as well as when comparing 65cm width to 35cm and 45cm apertures ($p<0.05$).

As previously reported, PCA individuals are less consistent in their action strategies during obstacle avoidance (Baker & Cinelli, 2014), therefore, it was hypothesized that the PCA group would be more variable in their control of SR than the NC for any given aperture width. If PCA individuals were more variable in their control of SR magnitude, it could be concluded that they were less precise at coupling their perceptions to appropriate actions (i.e., suggesting visuomotor deficits). The variability of SR magnitude was calculated by determining the SD of rotation magnitudes for each participant across three trials at each of the aperture widths, for all four VR environments. Mauchly's Test of Sphecirity was violated, therefore Greenhouse-Geisser correction was used for all outcomes. Analysis of SR magnitude variability (standard deviation across trials) at time of crossing revealed no significant main effects of aperture (F=0.860, p=0.511, n^2 =0.038, β=0.298), group (F=0.277, p=0.604, n^2 =0.012, β=0.080) or interactions between VR environment and group (F=1.365, p=0.266, n^2 =0.058, β=0.279) or aperture and group (F=1.596, p=0.177, n^2 =0.068, β=0.496) (Figure 8). The main effect of VR environment depicts a trend (F=3.168, p=0.051, n^2 =0.126, β=0.580), as the two groups began to perform more similarly within the Movement VR environment when compared to the Empty VR environment.

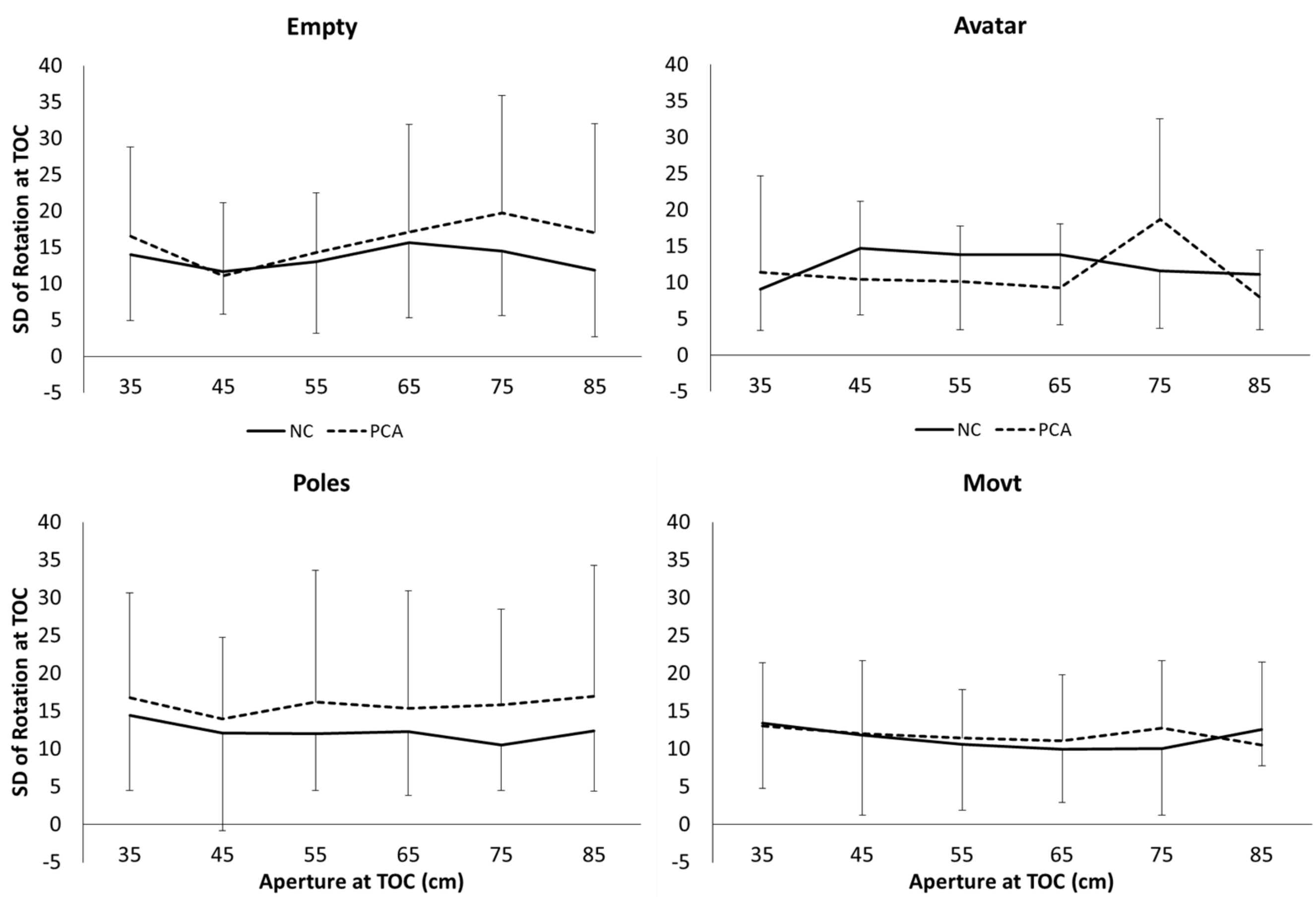

Figure 8: Variability (SD) of rotation magnitude at time of crossing for each of the peripheral VR environments represented by group (solid black representing Non-concussed, dashed representing Previously concussed, asymptomatic). No significant differences were found between groups, apertures, or VR peripheral environments.

In addition, the rate of SR (degrees/s) from onset of rotation to time of crossing (for trials in which a SR occurred) was calculated. It was expected that if participants maintained a constant onset of rotation, it would cause an increase in rate of rotation for smaller aperture widths to facilitate the modulation of SR to the aperture size presented. Mauchly's Tests of Sphericity was violated, thus Greenhouse-Geisser correction was used. The results revealed a main effect of VR environment ($F=3.151$, $p=0.049$, $n^2=0.125$, $\beta=0.598$). Pairwise comparisons depicted no significant differences between VR environments ($p>0.05$). There was no significant effect of aperture width ($F=1.677$, $p=0.201$, $n^2=0.071$, $\beta=0.323$), group ($F=0.481$, $p=0.495$, $n^2=0.021$, $\beta=0.102$), or interactions between VR environment and group ($F=2.018$, $p=0.141$, $n^2=0.084$, $\beta=0.411$) or aperture and group ($F=1.114$, $p=0.335$, $n^2=0.048$, $\beta=0.226$) (Figures 9 and 10).

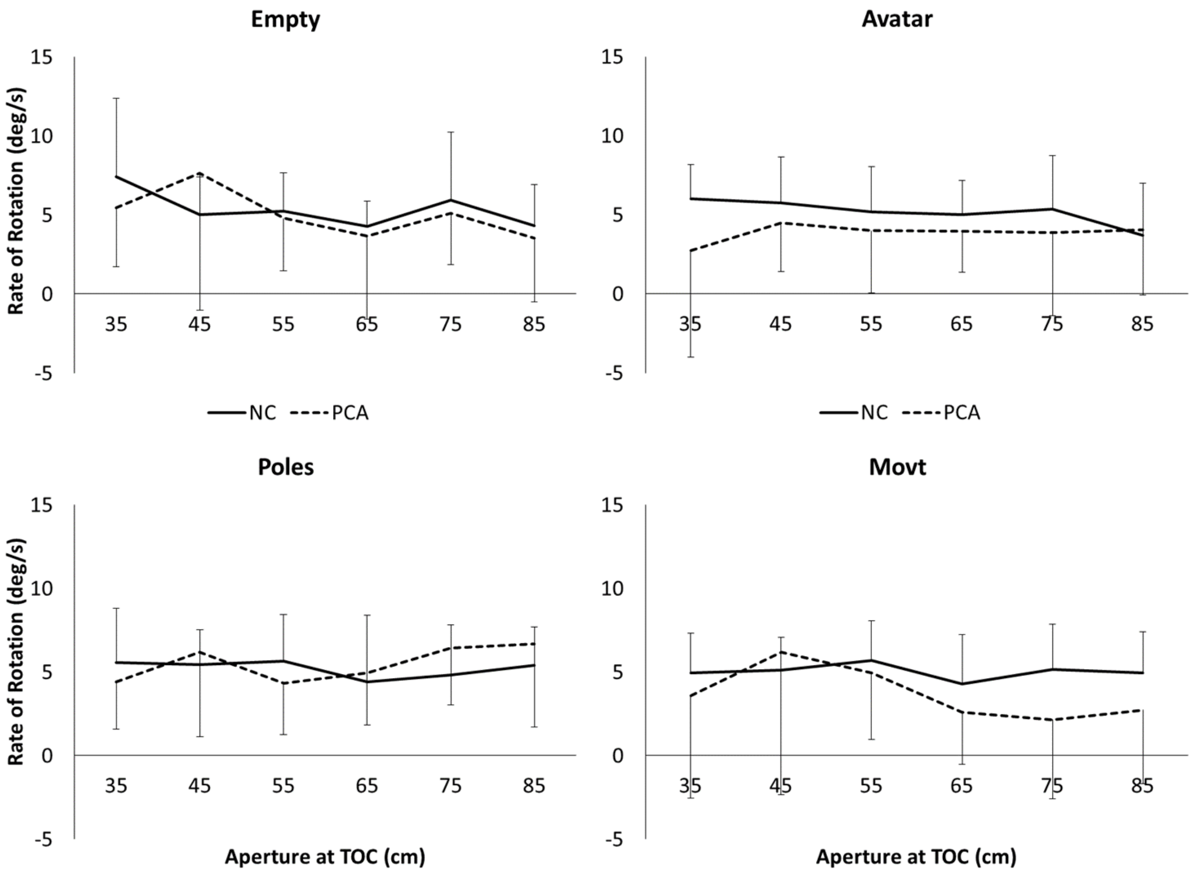

Figure 9: Rate of Rotation (degrees/sec) for each condition represented by group (solid black representing Non-concussed, dashed representing Previously concussed, asymptomatic). No significant differences were found between groups or aperture size. A main effect of VR environment was found ($p<0.05$).

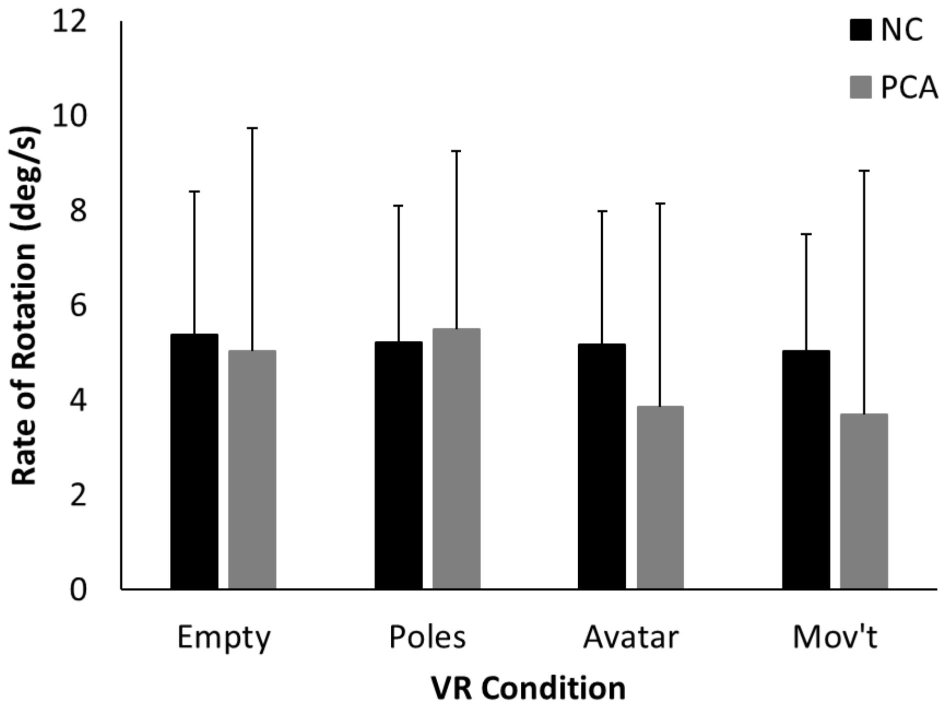

Figure 10: Rate of Rotation (degrees/sec) for each condition represented by group (black representing Non-concussed, gray representing Previously concussed, asymptomatic) and collapsed across aperture widths. A main effect of VR environment was found ($p<0.05$), with pairwise comparisons depicting no significant differences between VR environments ($p>0.05$)

Speed (instantaneous calculation)

Gait speed (cm/s) during the Approach was calculated to determine if the peripheral VR environment had an effect on the participants' actions. It was hypothesized that participants would have an increase in gait speed during Phase 2 (avatars) compared to Phase 1 (poles and empty environment) due to an increase in feelings of immersion and increased sense of urgency. The results indicated a main effect of VR environment ($F=4.056$, $p=0.019$, $\eta^2=0.156$) with pairwise comparisons revealing a difference in gait speed during Movement condition from the Empty, Poles, and Avatar conditions ($p=0.018$, $p=0.043$, and $p=0.011$ respectively) (Figure 11). There were no significant effects of aperture ($F=1.138$, $p=0.326$) or group (F=0.161, p=0.692), or interaction between group and VR environment (F=1.079, p=0.354) or between group and aperture width (F=2.035, p=0.148).

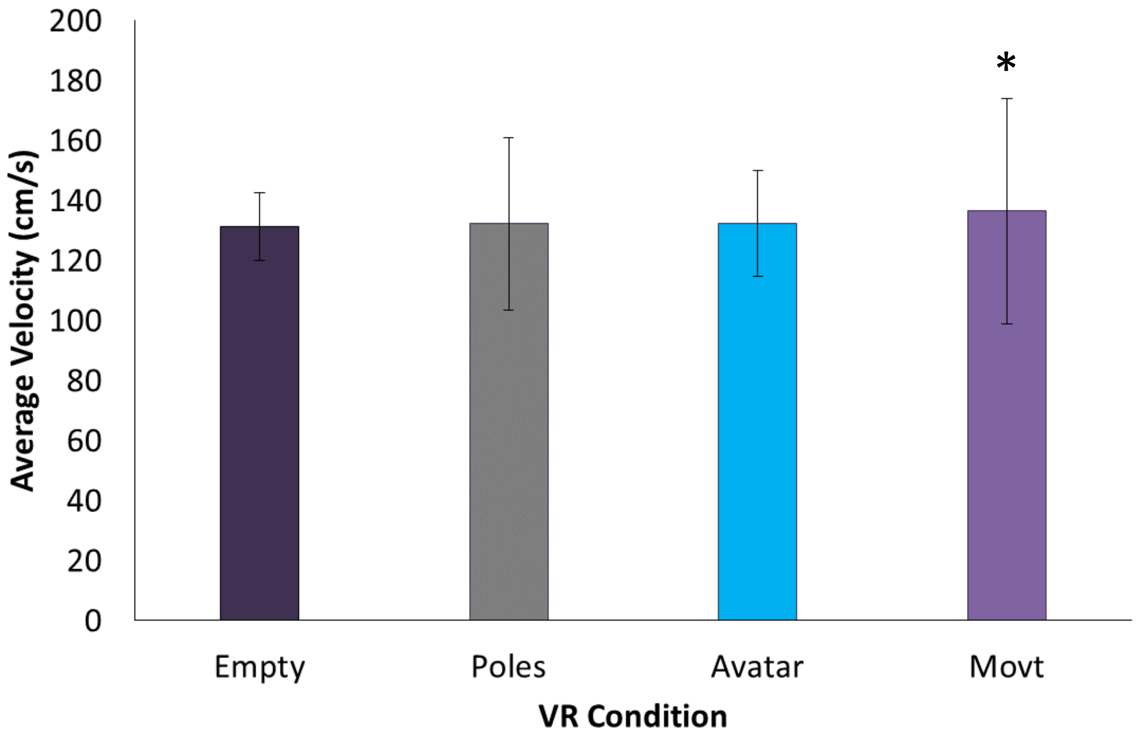

Figure 11: Approach velocity (cm/s) was found to increase in the Movement condition compared all other conditions ($p<0.05$) regardless of aperture width and group.

Difference in average walking speed from the Approach phase to the Crossing phase was assessed. It was hypothesized that the PCA group would display a greater difference in walking speed between Approach and Crossing phases due to a need for more time to make a decision regarding aperture size in Avatar and Movement VR environments as these conditions posed a greater perceptual challenge. Mauchly's Test of Sphericity was violated for aperture width; therefore Greenhouse-Geisser correction was used. Results indicated that there were no significant effects of VR environment (F=1.249, p=0.298, n^2=0.054, β=0.266), aperture (F=2.149, p=0.114, n^2=0.089, β=0.475), group (F=0.855, p=0.365, n^2=0.037, β=0.143) or interactions between VR environment and group (F=0.545, p=0.594, n^2=0.024, β=0.137) or aperture and group (F=2.570, p=0.078, n^2=0.102, β=0.542) (Figure 12).

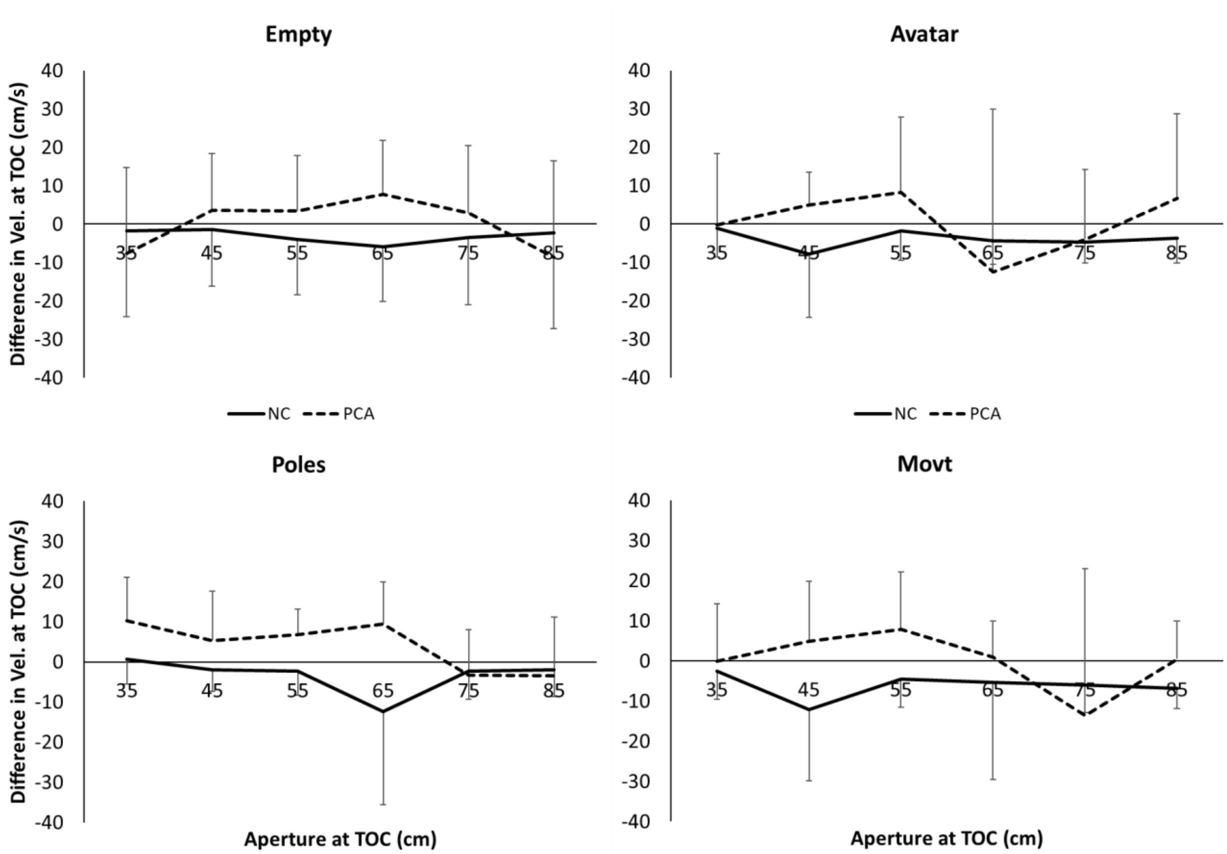

Figure 12: Differences in velocity (cm/s) from Approach to Crossing for each of the peripheral VR environments represented by group (solid black representing Non-concussed, dashed representing Previously concussed, asymptomatic). No significant differences were found between groups, apertures, or VR peripheral environments.

The CVV was calculated during the Approach phase. It was hypothesized that the PCA group would be more affected by the peripheral Movement VR environment causing greater changes (variability) in approach speed. Mauchly's Test for Sphericity was violated for all measures, thus Greenhouse-Gessier correction was used. The results revealed no main effect of aperture width (F=0.719, p=0.545, n^2=0.032, β=0.196), VR environment (F=1.909, p=0.175, n^2=0.080, β=0.309), or group (F=1.231, p=0.279, n^2=0.053, β=0.186). As well, there was no interaction between group and VR environment (F=0.737, p=0.440, n^2=0.032, β=0.145) or between group and aperture width (F=1.372, p=0.259, n^2=0.059, β=0.350) (Figure 13).

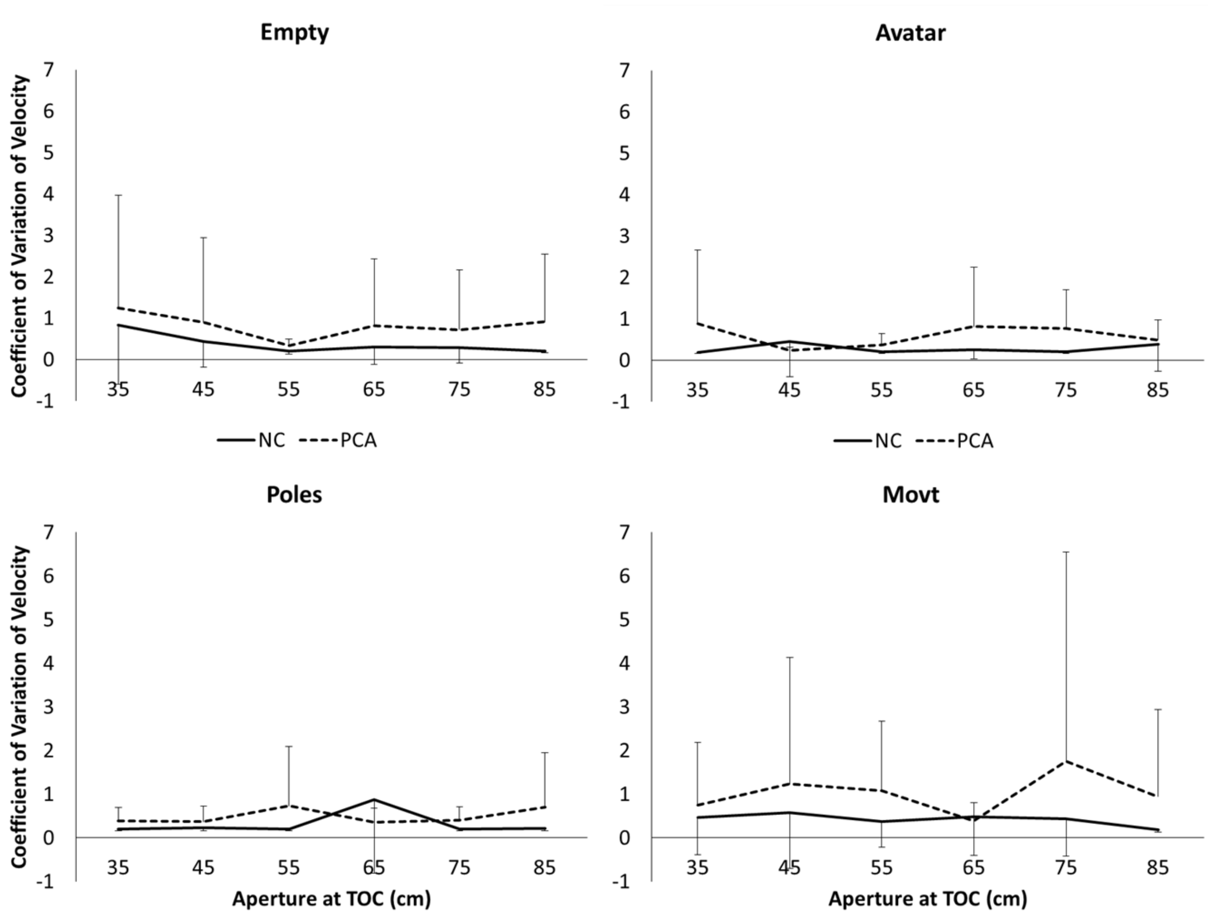

Figure 13: Coefficient of variation of velocity for each condition represented by group (solid black representing Non-concussed, dashed representing Previously concussed, asymptomatic). Higher numbers indicate increase in velocity fluctuations across trials. No significant effects or interactions were found.

Medial-lateral centre of mass variability (cm)

ML COM variability, during forward progression of the Approach phase, is an indicator of dynamic stability during locomotion and has been previously correlated with aperture crossing behaviours such that larger magnitudes of ML COM variability required larger apertures for passage (Hackney & Cinelli, 2013). This measure was used to determine if the PCA group was more affected (i.e., larger ML COM variability in the absence of obstacle avoidance, decreased stability) by the peripheral visual stimuli compared to the NC. Mauchly's Test of Sphericity was violated for all measures; therefore Greenhouse-Geisser correction was used. Results indicated that there were no significant effects of VR environment ($F=2.621$, $p=0.075$, $n^2=0.106$, $\beta=0.534$), aperture size ($F=1.012$, $p=.414$, $n^2=0.044$, $\beta=0.205$), group ($F=1.217$, $p=0.282$, $n^2=0.052$, $\beta=0.184$), or interactions between VR environment and group ($F=1.097$, $p=0.348$, $n^2=0.047$, $\beta=0.246$), or aperture and group ($F=0.996$, $p=0.371$, $n^2=0.043$, $\beta=0.203$) (Figure 14).

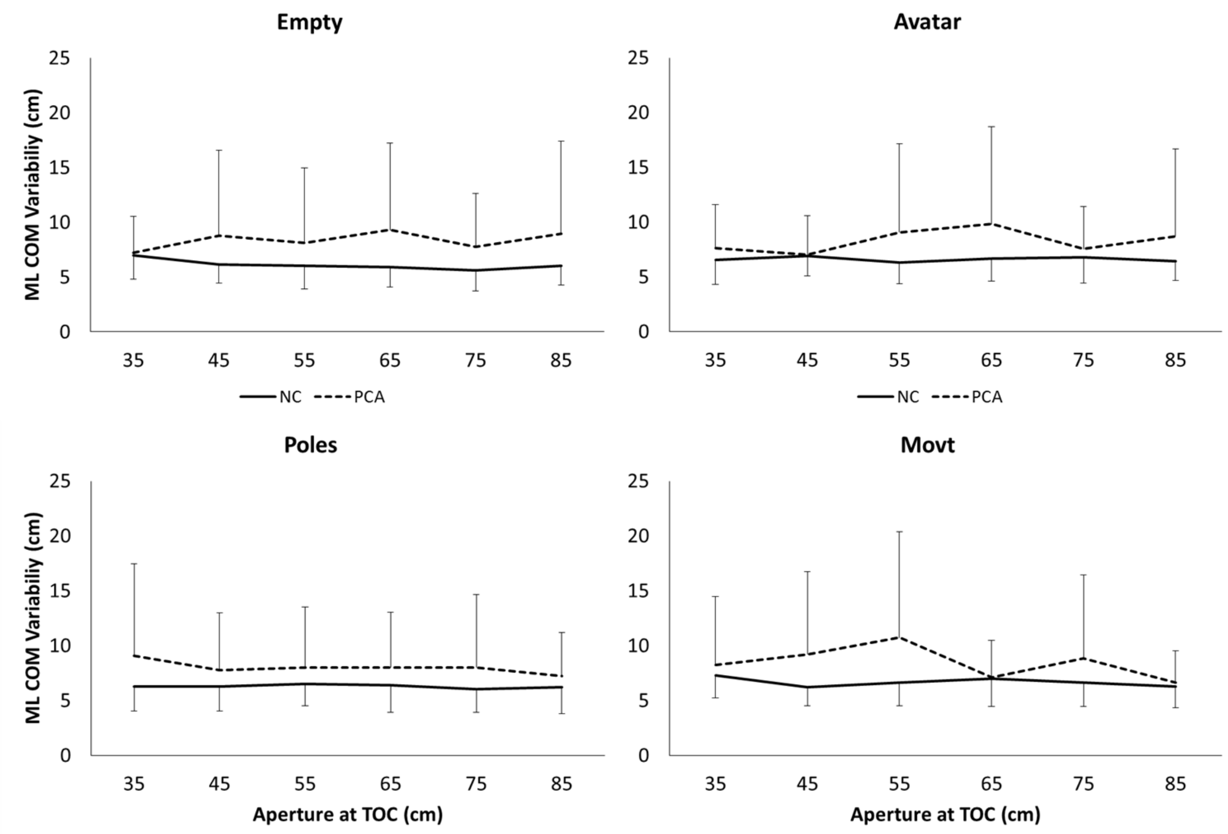

Figure 14: ML COM variability (cm) during the Approach for each final aperture represented by group (solid black representing Non-concussed, dashed representing Previously concussed, asymptomatic). No significant effect of VR environment or aperture on participants' dynamic stability.

Relationship between time since concussion recovery and actions

Further analyses were conducted to determine if time since concussion recovery correlated with variability of the magnitude of SR at time of crossing for each PCA's individual theoretical critical point (i.e., switch point) (Figure 15). Aperture widths were collapsed across VR environments as there was no significant difference in SR magnitude variability between environments. Tests of normality determined the sample was not normally distributed. Pearson product-moment correlations were run to determine the relationship between time since recovery and magnitude of SR within each of the VR environments. There were no significant correlations found between time since recovery and

SR magnitude within Empty VR (r=0.288, p=0.365), Poles VR (r=0.437, p=0.156), Avatar VR (r=0.492, p=0.104), or Movement VR (r=0.250, p=0.434).

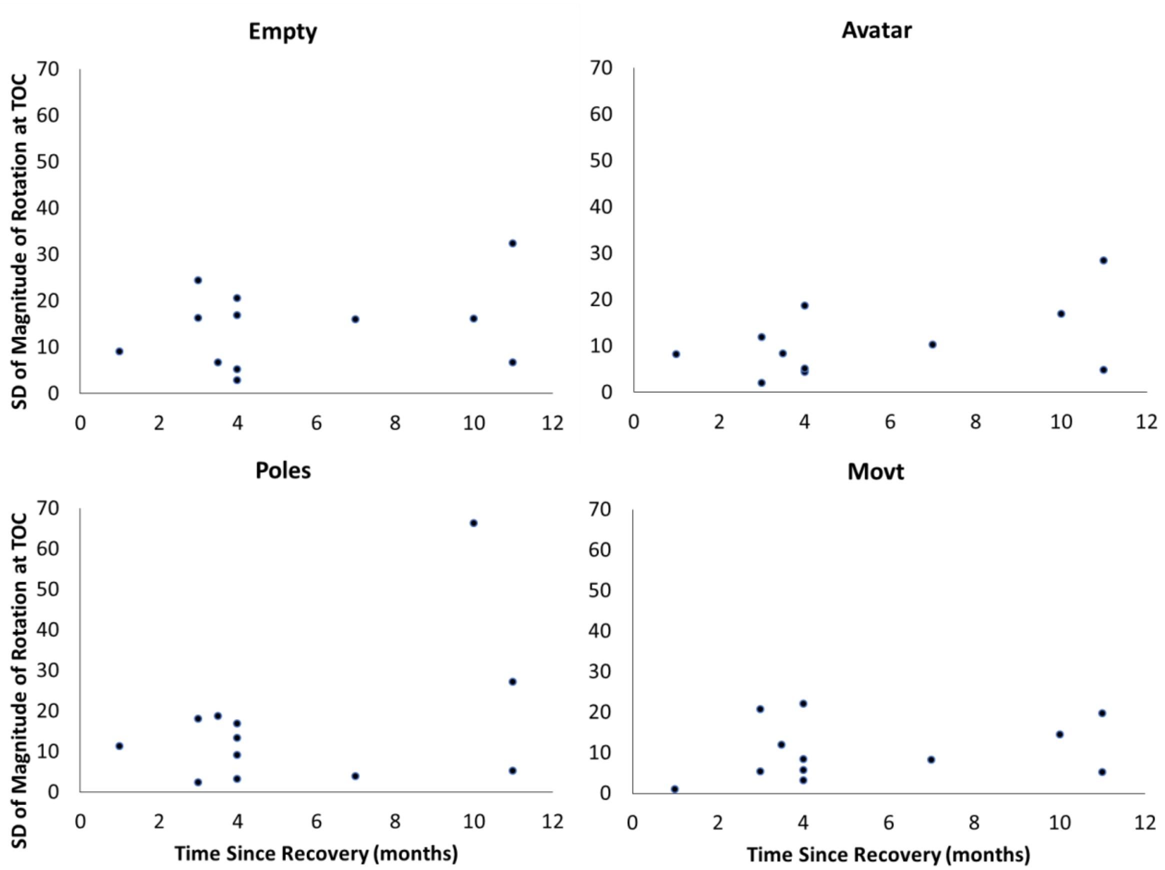

Figure 15: Relationship between time since concussion and variability in shoulder rotation magnitude at theoretical critical point for each VR environment. No significant correlations were found (p>0.05).

CHAPTER IV: Discussion

The objective of the current study was two-fold: 1) to investigate the extent to which one's behaviours on a central field of view collision avoidance task are influenced by the amount of peripheral movement in virtual reality; and 2) to determine whether recently concussed asymptomatic (PCA) individuals behaved differently than non-concussed (NC) individuals. We defined peripheral visual stimuli as a technique in which objects located within a participant's peripheral field of view were manipulated to be absent, stationary/relatively stationary (veridical optic flow), or move independent of the participant's movements (non-veridical optic flow). The current study utilized the closing doors of a virtual subway train to create an aperture for passage. The task was designed to mimic real world situations in which the environment may have increasing amounts of peripheral visual stimuli. It was expected that a critical point (i.e., when the limits of action are reached and a transition phase into a different action occurs (Warren & Whang, 1987)) would emerge, which would be impacted by the different levels of peripheral visual environment, eliciting a change in critical point. Furthermore, it was anticipated that PCA individuals would elicit different behaviours compared to NC counterparts (Baker & Cinelli, 2014), as a product of the peripheral visual environment. The main finding from the study was that individuals produced significantly larger shoulder rotations at smaller apertures (i.e., 35, 45, and 55cm) than the largest aperture. However, this effect was mostly driven by NC individuals, as PCA individuals do not appear to modulate SR to aperture size (Figure 7). Interestingly, trends within the data appear to reveal an effect of VR environment on participant behaviours, such that groups perform more similarly within the Movement VR condition when examining variability of SR (Figure 8) and rate of rotation (Figure 10). These findings suggest that the PCA group may perform better in VR environments with increased sense of immersion and visual information.

Do participants demonstrate a change in action as aperture widths change?

When examining perception-action integration, a cyclical relationship is highlighted through affordance theory. However, this relationship is incomplete without the consideration of task constraints which are imperative to how and what action strategies an individual may employ to successfully complete the task (Warren, 2006). Successful completion of a task is the product of multiple factors; the individual must account for the environment, their personal action capabilities, as well as the constraints of the task itself (i.e., instructions from the experimenter). The inclusion of task constraints into the understanding of affordance theory provides a comprehensive representation of how individuals integrate perception and action through behavioural dynamics (Fajen & Warren, 2003; Warren, 2006). Within the present study, the experimental instructions to board the subway train without colliding with the doors could be broken down into two parts. The subway train, as the goal, is an attractor, while the closing doors act as repellers. It was hypothesized that for aperture widths less than or equal to 1.3x the participant's SW (i.e., shrinking gap between doors at time of crossing), a SR would be elicited to reduce one's medial/lateral width and avoid a collision with the doors (Hackney & Cinelli, 2011; Warren & Whang, 1987). It was believed that higher critical point values would be observed as the peripheral visual environment became more complex.

Both PCA and NC individuals executed SR regardless of aperture width at time of crossing. However, participants modulated the degree of rotation to the aperture size, performing larger rotations for widths of 35, 45, and 55cm (less than 1.45 x average SW) compared to 85cm (Figure 7). Interestingly, NC executed greater rotations at 55cm widths compared to 85cm width; a modulation not found within the PCA group. Although the SR for the smaller apertures were significantly greater than the SR for the largest aperture, the difference between these magnitudes does not suggest that individuals display a critical point that is body-scaled. The smallest SR magnitude (at 85 cm) was still much larger than those produced during straight walking (i.e., 40 degrees vs. ~5 degrees) and the difference between the largest and smallest SR magnitudes was approximately 10 degrees. Previous work by Fath & Fajen (2011) found that participants executed shoulder rotations to decrease body width and allow for passage of static apertures in virtual reality by systematically increasing the angle of rotation as the size of the aperture decreased. The researchers determined the range of SR magnitude to span greater than 30 degrees when comparing aperture sizes of 0.95x to 1.85x participant SW; a behaviour which is missing from the currently study. Although a significant difference in SR was detected within the current study, it appears as though participants implemented a conservative “one solution fits all” strategy, where SR were employed universally across aperture size with minor adjustments. This conservative strategy is reflective of actions employed by older adults for successful obstacle clearance during gait. Researchers found that when older adults had to step over an obstacle, they modulated the lead foot toe clearance to obstacle height to ensure safer crossing. However unlike with the lead limb, visual cues were unavailable during trail limb crossing thus toe clearance was not modulated to obstacle height (Lu, Chen, & Chen, 2006). Older adults chose to implement a more conservative strategy in the trailing limb toe clearance. Participants in the current study appear to have adopted a strategy which was determined *a priori*, similar to previous studies with static apertures (Hackney & Cinelli, 2013; Higuchi, 2013). This behaviour may be a result of receiving information regarding onset of door closure within the final meter before the doors. Participants may not have been able to account for the rate of door closure, and instead selected an action they knew to be successful.

A change in action strategy did occur as apertures increased to 65cm or greater (1.45 x average SW or greater), but it may be best interpreted as slight modification to a "standard" degree of rotation, rather than a true critical point. In contrast to previous research, which identified 1.3 times one's widest body dimension as the point in which a change in action strategy occurs in static aperture situations (Hackney, Vallis, & Cinelli, 2013; Warren & Whang, 1987), it appears as though two separate groups of apertures have emerged, such that the behaviours for the smallest three apertures were different from the largest three apertures. The NC group executed slightly larger SR for the small aperture group (35, 45, and 55cm) than with the large aperture group (65, 75, and 85cm); a trend not seen in the PCA group. However, further investigation into this relationship relative to rate of rotation was inconclusive. It was expected that participants would control their rate of rotation relative to door movement, such that smaller apertures would elicit a faster rate of rotation. In contrast, participants rotated at a constant rate regardless of aperture width. Significant differences were found between peripheral environments, with rates of rotation appearing to be greater in the Avatar and Movement VR environments compared to the Empty and Poles (Figure 8).

This difference is likely due to order of presentation (Phase 1 vs. Phase 2) as participants became more familiar with the task and VR environment. The constant rate of rotation across aperture widths further supports the "one solution fits all" hypothesis, as individuals did not modulate SR to the onset of door closure.

It is possible that during collision avoidance tasks in virtual reality, individuals are unable to couple their own physical size with the VR environment due to the lack of peripheral body information (i.e., shoulder width). According to Mohler, Creem-Regehr, Thompson, and Bülthoff (2010), awareness of one's body based information provides a frame of reference of body position in space as well as a metric for scaling through visuomotor feedback while moving. Therefore, a lack of peripheral body information in the current study may have led to an inability of participants to perceive the affordances of the aperture of the subway train, leading to a more conservative approach. This is reflective of previous work in which judgements of distance travelled within VR environment using a HMD were more accurate in the presence of avatar-based body, regardless of reliability of motion. Distance travelled estimation were found to be more accurate when participants had availability of tracked body-part avatars (i.e., avatar-based body which mimicked real time movements of the individual) compared to no avatar (i.e., no visual representation of body in space, standard use of HMD based VR environments) which tended to offer distance underestimation (Mohler, Creem-regehr, Thompson, & Bulthoff, 2010), consistent with a more conservative approach. This provides insight into the imperative role of visuomotor control during locomotion and the role of embodied perception in VR environments. Thus, when considering the current study in which individuals were forced to pass through a closing aperture within a VR environment, it appears that a more conservative approach (i.e., execution of shoulder rotations at all aperture widths) was employed to ensure success and safety during aperture crossing in the absence of self-representation.

Does variability of SR magnitude change with time since concussion recovery?

Research by Baker & Cinelli (2014) demonstrated that previously concussed individuals, minimum 30 days post injury, are more variable in their actions compared to non-concussed controls in obstacle avoidance. It has previously been recognised that individuals who have recently sustained a concussion demonstrate highly variable actions during visuomotor integration tasks (Slobounov et al., 2006), while young adults are consistent and accurate in their dynamic stability and visuomotor strategies (Hackney & Cinelli, 2013; Hackney et al., 2013; Lee & Lishman, 1975; Patla, 1997). Therefore, it was expected that as time since recovery increased, variability in SR during an aperture crossing task would decrease at each individual's theoretical critical point (i.e., aperture closest to 1.3x SW). It was determined that no significant relationships exist between time since recovery of concussion and SR variability at time of crossing for each VR environment. This may be due to the nature of the sample of PCA individuals recruited for the study. The majority of participants were between three and four months since concussion, which does not give an accurate representation of a timeline of recovery. An increase in the sample size of a large variety of recovery time points may help to tease out this relationship further and provide a more accurate depiction of the relationship between these factors. In addition, NC individuals were found to have similar SR variability within the task which may be a product of the information available due nature of the task itself.

Did participant approach speed increase as a result of increased peripheral visual stimuli?

Speed was assessed both during the Approach phase (start of movement to 2m prior to aperture crossing) and the Crossing phase (0.5m prior to aperture to time of crossing). It was hypothesized that participants would display an increase in the Approach speed between Phase 1 (Empty and Poles) and Phase 2 (Avatar and Movement), due to the inclusion of avatars creating a more immersive setting and an increase in the sense of urgency to reach the goal. Participants demonstrated an increase in gait speed of 4.5cm/s during the Movement VR when compared to the other three VR environments (Figure 11). One reason for this finding could be that individuals adjust speed sub-consciously as a result of non-veridical optic flow information. The margin of increase in speed was not great enough to surpass threshold of detection and thus participants would not have recognized that they were walking faster during the Movement condition. However, the modest effect size highlights the limited interpretation of this finding. Participants may have experienced this slight increase due to a more "real world" effect with the introduction of avatar movement within the subway station VR environment. It is known that individuals walk slower and have a shorter stride length when locomoting within VR compared to real world space (Mohler, Campos, Weyel, & Bulthoff, 2007), however this study was conducted within a virtual space which did not include the use of objects or avatars to increase feelings of immersion. Previous research has shown that behaviours of individuals when passing through stationary poles and people in the real world (Hackney, Cinelli, Warren, & Frank, 2015), were not replicated when individuals had to pass through stationary poles and avatars in VR environments (Hackney et al., 2015). Similarities are seen with the current study, as the gait behaviours of participants were constant between conditions with poles and stationary avatars. Once the avatars moved randomly, gait speed of the participant increased. This change in behaviour may be due to the increase in "human-like" characteristics of the moving avatars. Pfaff & Cinelli (2017) suggested the lack of difference between avoidance behaviours of avatars and poles may be due to a decrease in "human-like" characteristics, as the avatar face is unrealistic. This theory was further supported as the researches found a difference in avoidance behaviours when comparing rear facing avatars to poles; a difference which was not evident when comparing forward facing avatars (Pfaff & Cinelli, 2017). As well, movement patterns of the avatars in Phase 2 of the current study were made to appear plausible in the subway train setting, thus avatars were programmed to approach the train doors near the participants' path to maintain the realistic nature of the task. Therefore, it is likely that the increased gait speed during the Movement VR was a result of a more realistic setting as avatars were attributed more "human-like" characteristics by the participants.

Do PCA individuals display greater differences in velocity between Approach and Crossing phases compared to NC individuals?

It was hypothesized that the PCA individuals would display a greater change in velocity between the Approach and Crossing compared to NC individuals as a result of requiring more time to decide the correction action required to pass through a given aperture. This difference was expected to be observed during the VR environments that posed greater perceptual challenge due to the inclusion of avatars (i.e., Phase 2 conditions). While there is no significant difference between groups across conditions, it is noted that NC individuals on average slowed down from Approach to Crossing (Figure 11). In comparison, PCA individuals were more variable within and between environments with change in gait speed from Approach to Crossing. It is difficult to draw true conclusions from this measure as the speed at the Crossing accounted for a much shorter time window (i.e., a single step) compared to the Approach phase, and certain behaviours could have been exaggerated. For instance, one participant temporarily increased walking speed across the aperture to ensure successful boarding of the subway train which was exaggerated given the short distance covered. Exaggerated and variable behaviours during the Crossing phase produced high variability for both groups, making it difficult to get a true representation of the action used to complete the task successfully. Allowing participants to navigate further onto the train may have reduced the constraints placed on the individual and allowed for a more fluid movement while boarding the train, in contrast to participants needing to stop once inside the doors due to reaching the perimeter of the collection space.

Do groups perform differently depending on the peripheral visual environment?

It was expected that participants would have the most accurate performance within the stationary peripheral visual stimuli condition as it would provide an environment rich in visual information (Warren et al., 2001). It was hypothesized that the PCA group would be more affected by the peripheral visual stimuli (non-veridical optic flow) compared to the NC, which would lead to an increase in ML COM variability (poor dynamic stability) during the Approach phase. Results revealed no effect of VR environments on participant dynamic stability. Further to this point, the visual peripheral stimuli, which were manipulated throughout the experiment, did not significantly influence participants' magnitude of SR, variability of SR, or speed behaviours during the task. This may be due to a variety of reasons. First, the field of view within which the random avatar movement was captured maybe have been too narrow to afford increase in perceived self-motion conflict. The forward progression of the participant towards the doors may have decreased the period of time in which the stimuli were visible, thus not capturing a true representation of the "random movement" for the entirety of the trial. In the future, the implementation of additional movement on the outside of the train, such as television screens depicting moving scenes, may help to resolve this issue as it will provide movement within the peripheral field of view as the participant boards the train. Second, perhaps the environment was not busy enough to make an impact of peripheral visual stimuli as a distractor and generate non-veridical optic flow. In the absence of peripheral body movement information, the reference point to self-motion is not available, thus individuals may not have detected an issue with the motion of the avatars surrounding them. Furthermore, in a solely visually driven scene, participants may rely more heavily upon the visual system, reducing the amount of information integrated from the vestibular and somatosensory systems and thus minimizing any potential effect of non-veridical optic flow. Next steps in this research area should include the addition of body-based avatars, similar to work of Mohler et al. (2010), to increase the full sense of immersion and provide a metric for visuomotor feedback. Providing the opportunity to integrate information from each of the systems more effectively within the VR setting may help to identify if the PCA individuals truly have an inability to successfully integrate information, which leads to the execution of inappropriate actions.

CHAPTER IV: Conclusion

This thesis assessed two populations on a perception-action integration task within a virtual reality environment. Previously concussed asymptomatic (PCA) individuals were not found to demonstrate speed, shoulder rotation variability, or dynamic stability differences when compared to non-concussed (NC) controls on this task. Nevertheless, NC individuals were found to execute slightly larger shoulder rotations for the small aperture group (35, 45, and 55cm) than with the large aperture group (65, 75, and 85cm); a behaviour absent from the PCA group. Both groups were found to employ a more conservative approach (i.e., execution of shoulder rotations at all aperture widths) within each of the peripheral visual environments. In the absence of visual peripheral body information, vestibular and somatosensory information regarding our body in space are not enough to provide accurate behavioural adjustments in obstacle avoidance. As a result, individuals rely on a "one solution fits all" strategy to ensure success during a closing aperture task. Therefore, it is evident that the capacity to integrate information from each of the sensory systems is an asset during locomotion as it provides us with the ability to navigate successfully through an environment.

This thesis did not provide strong evidence to support the theory of visuomotor deficits in PCA individuals through the current paradigm. These findings suggest that minor differences in visuomotor control may exist between PCA and NC individuals; however, a more comprehensive sample of individuals of various time points since concussion recovery may provide further insight. Future research that includes the use of peripheral body information may assist in determining a timeline of recovery for these visuomotor deficits, in addition to furthering the understanding of the behaviours demonstrated by each group.

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CHAPTER VI

Appendix A

The DOSPERT Scale (from Blais, & Weber, 2006)

To generate a short version of the scale with items that would be interpretable by a wider range of respondents in different cultures, the 40 items of the original scale (Weber, Blais, & Betz, 2002) were revised and eight new items were added. The response scale was modified slightly by increasing the number of scale points from 5 to 7 and by labeling all of them (i.e., instead of just the two endpoints) in an effort to increase the psychometric quality of the scale (Visser, Krosnick, & Lavrakas, 2000). The new set of 48 items was administered to a group of 372 North Americans, and this group was randomly split into two sub-groups. Data from one sub-group were analyzed in an exploratory manner and resulted in a 30-item model that was tested through confirmatory factor analyses using the other sub-group (Blais, & Weber, 2005).

The *risk-taking* responses of the 30-item version of the DOSPERT Scale evaluate behavioral intentions -or the likelihood with which respondents might engage in risky activities/behaviors- originating from five domains of life (i.e., ethical, financial, health/safety, social, and recreational risks), using a 7-point rating scale ranging from 1 (*Extremely Unlikely*) to 7 (*Extremely Likely*).[1] Sample items include “Having an affair with a married man/woman” (*Ethical*), “Investing 10% of your annual income in a new business venture” (*Financial*), “Engaging in unprotected sex” (*Health/Safety*), “Disagreeing with an authority figure on a major issue” (*Social*), and “Taking a weekend sky-diving class” (*Recreational*). Item ratings are added across all items of a given subscale to obtain subscale scores. Higher scores indicate greater risk taking in the domain of the subscale.

The *risk-perception* responses evaluate the respondents’ gut level assessment of how risky each activity/behavior is, using a 7-point rating scale ranging from 1 (*Not at all*) to 7 (*Extremely Risky*). Item ratings are added across all items of a given subscale to obtain subscale scores, with higher scores suggesting perceptions of greater risk in the domain of the subscale.

The internal consistency reliability estimates associated with the original 48-item English risk-taking scores ranged from .70 to .84 (mean $\alpha = .78$), and those associated with the risk-perception scores, from .70 to .81 (mean $\alpha = .77$), as reported by Weber, et al. (2002). The authors also found moderate test-retest reliability estimates (albeit for an earlier version of the instrument) and provided evidence for the factorial and convergent/discriminant validity of the scores with respect to constructs such as sensation seeking, dispositional risk taking, intolerance for ambiguity, and social desirability. Construct validity was also assessed via correlations with the results of a risky gambling task as well as with tests of gender differences.

[1] The six financial items can be split into three gambling and three investment items for further decomposition of the construct. Conversely, all 30 items can be added up, yielding an overall scale score, for a broader assessment of the risk-taking constructs. These models were also tested through confirmatory factor analyses (Blais, & Weber, 2005, 2006).

Domain-Specific Risk-Taking (Adult) Scale – Risk Taking

For each of the following statements, please indicate the **likelihood** that you would engage in the described activity or behavior if you were to find yourself in that situation. Provide a rating from *Extremely Unlikely* to *Extremely Likely*, using the following scale:

1	2	3	4	5	6	7
Extremely Unlikely	Moderately Unlikely	Somewhat Unlikely	Not Sure	Somewhat Likely	Moderately Likely	Extremely Likely

1. Admitting that your tastes are different from those of a friend. (S)
2. Going camping in the wilderness. (R)
3. Betting a day's income at the horse races. (F/G)
4. Investing 10% of your annual income in a moderate growth mutual fund. (F/I)
5. Drinking heavily at a social function. (H/S)
6. Taking some questionable deductions on your income tax return. (E)
7. Disagreeing with an authority figure on a major issue. (S)
8. Betting a day's income at a high-stake poker game. (F/G)
9. Having an affair with a married man/woman. (E)
10. Passing off somebody else's work as your own. (E)
11. Going down a ski run that is beyond your ability. (R)
12. Investing 5% of your annual income in a very speculative stock. (F/I)
13. Going whitewater rafting at high water in the spring. (R)
14. Betting a day's income on the outcome of a sporting event (F/G)
15. Engaging in unprotected sex. (H/S)
16. Revealing a friend's secret to someone else. (E)
17. Driving a car without wearing a seat belt. (H/S)
18. Investing 10% of your annual income in a new business venture. (F/I)
19. Taking a skydiving class. (R)
20. Riding a motorcycle without a helmet. (H/S)
21. Choosing a career that you truly enjoy over a more secure one. (S)
22. Speaking your mind about an unpopular issue in a meeting at work. (S)
23. Sunbathing without sunscreen. (H/S)
24. Bungee jumping off a tall bridge. (R)
25. Piloting a small plane. (R)
26. Walking home alone at night in an unsafe area of town. (H/S)
27. Moving to a city far away from your extended family. (S)
28. Starting a new career in your mid-thirties. (S)
29. Leaving your young children alone at home while running an errand. (E)
30. Not returning a wallet you found that contains $200. (E)

Note. E = Ethical, F = Financial, H/S = Health/Safety, R = Recreational, and S = Social.

Domain-Specific Risk-Taking (Adult) Scale – Risk Perceptions

People often see some risk in situations that contain uncertainty about what the outcome or consequences will be and for which there is the possibility of negative consequences. However, riskiness is a very personal and intuitive notion, and we are interested in **your gut level assessment of how risky** each situation or behavior is.

For each of the following statements, please indicate **how risky you perceive** each situation. Provide a rating from *Not at all Risky* to *Extremely Risky*, using the following scale:

1	2	3	4	5	6	7
Not at all Risky	Slightly Risky	Somewhat Risky	Moderately Risky	Risky	Very Risky	Extremely Risky

Domain-Specific Risk-Taking (Adult) Scale – Expected Benefits

For each of the following statements, please indicate **the benefits** you would obtain from each situation. Provide a rating from **1 to 7**, using the following scale:

1	2	3	4	5	6	7
No benefits At all			Moderate Benefits			Great Benefits

Reference:

Blais, A-R. and E. U. Weber. 2006. “A Domain-specific Risk-taking (DOSPERT) Scale for Adult Populations.” *Judgment and Decision Making, 1*, 33-47.

Scoring Instructions for the DOSPERT Scale (from Blais & Weber, 2006)

1. The DOSPERT scale contains three separate response scales: 'Risk-Taking', 'Risk-Perceptions', and 'Expected Benefits'. Coefficients from the latter two can be used to assess risk-attitude (see "Risk attitude within a risk-return framework" on page 2). Each response scale uses the same items from the five or six domain subscales show in Table 1 below.

2. Each DOSPERT scale item is labeled 'E', 'F' (see *Note*), 'H/S', 'R', or 'S' (remove these labels prior to administering DOSPERT to participants). These letters indicate the subscale to which the item belongs. E = Ethical, F = Financial, H/S = Health/Safety, R = Recreational, and S = Social. *Note:* Optionally, the six financial items can be split into three gambling items (F/G) and three investment items (F/I).

3. Add rating scores across all items of a given subscale (i.e. 'E', "F', 'H/S', 'R', or 'S') to obtain the domain score. Either use this sum or divide the domain score by the number of items (i.e. three or six) in the given subscale.

Table 1

Domain subscale	Item text
Ethical (E)	6. Taking some questionable deductions on your income tax return. (E)
	9. Having an affair with a married man/woman. (E)
	10. Passing off somebody else's work as your own. (E)
	16. Revealing a friend's secret to someone else. (E)
	29. Leaving your young children alone at home while running an errand. (E)
	30. Not returning a wallet you found that contains $200. (E)
Financial (Investment/Gambling) (F/I, F/G)	12. Investing 5% of your annual income in a very speculative stock. (F/I)
	4. Investing 10% of your annual income in a moderate growth mutual fund. (F/I)
	18. Investing 10% of your annual income in a new business venture. (F/I)
	3. Betting a day's income at the horse races. (F/G)
	14. Betting a day's income on the outcome of a sporting event (F/G)
	8. Betting a day's income at a high-stake poker game. (F/G)
Health/Safety (H/S)	5. Drinking heavily at a social function. (H/S)
	15. Engaging in unprotected sex. (H/S)
	17. Driving a car without wearing a seat belt. (H/S)
	20. Riding a motorcycle without a helmet. (H/S)
	23. Sunbathing without sunscreen. (H/S)
	26. Walking home alone at night in an unsafe area of town. (H/S)
Recreational (R)	2. Going camping in the wilderness. (R)
	11. Going down a ski run that is beyond your ability. (R)
	13. Going whitewater rafting at high water in the spring. (R)
	19. Taking a skydiving class. (R)
	24. Bungee jumping off a tall bridge. (R)
	25. Piloting a small plane. (R)
Social (S)	1. Admitting that your tastes are different from those of a friend. (S)
	7. Disagreeing with an authority figure on a major issue. (S)

	21. Choosing a career that you truly enjoy over a more prestigious one. (S)
	22. Speaking your mind about an unpopular issue in a meeting at work. (S)
	27. Moving to a city far away from your extended family. (S)
	28. Starting a new career in your mid-thirties. (S)

<u>Scoring instructions for risk—return interpretation of domain-specific risk-taking scale</u>
Risk attitude can be conceptualized in the risk-return framework of risky choice used in finance. In this framework, people's preference for risky options is assumed to reflect a tradeoff between an option's expected benefit, usually equated to expected value (EV), and its riskiness. In finance, riskiness of an option is equated to its variance, but psychological risk-return models treat perceived riskiness as a variable that can differ between individuals and as a function of content and context:

$$\text{Preference (X)} = a(\text{Expected Benefit(X)}) + b(\text{Perceived Risk(X)}) + c$$

1. To find the coefficients *a*(Expected Benefit(X)) and *b*(Perceied Risk(X)), regress "Expected Benefits" and "Risk-Perceptions" on "Risk-Taking" for each participant, using corresponding scores from each item, as shown in Table 2 below. *Note:* A positive coefficient *b* indicates <u>risk-seeking</u> behavior and a negative coefficient *b* indicates <u>risk-aversion</u> behavior.
2. Calculate risk-attitude using the formula above.

<u>DOSPERT data in ANOVA or general linear model</u>
Some groups may differ in risk-perceptions and expected benefits. Get the coefficients *a*(Expected Benefits(X)) and *b*(Perceived Risk(X)) for each participant and use them as dependent measures. Analyze using ANOVA or a general linear model.

Table 2

Domain subscale	X	*a*(Expected Benefits(X))	*b*(Perceived Risk(X))
Ethical (E)	6. Taking some questionable deductions on your income tax return. (E)	*a*(Expected Benefits score for item #6)	*b*(Perceived Risk score for item #6)
	9. “”	“”	“”
	10. “”	“”	“”
	16. “”	“”	“”
	29. “”	“”	“”
	30. “”	“”	“”
Financial (Investment/Gambling) (F/I, F/G)	12. “”	“”	“”
	4. “”	“”	“”
	18. “”	“”	“”
	3. “”	“”	“”
	14. “”	“”	“”
	8. “”	“”	“”
Health/Safety (H/S)	5. “”	“”	“”
	15. “”	“”	“”
	17. “”	“”	“”
	20. “”	“”	“”
	23. “”	“”	“”

	26. “”	“”	“”
Recreational (R)	2. “”	“”	“”
	11.””	“”	“”
	13. “”	“”	“”
	19. “”	“”	“”
	24. “”	“”	“”
	25. “”	“”	“”
Social (S)	1. “”	“”	“”
	7. “”	“”	“”
	21. “”	“”	“”
	22. “”	“”	“”
	27. “”	“”	“”
	28. Starting a new career in your mid-thirties. (S)	*a*(Expected Benefits score for item #6)	*b*(Perceived Risk score for item #28)

Appendix B

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. PARTICIPANTS MAY CHOOSE TO NOT PROVIDE A RESPONSE TO ANY QUESTION THEY CHOOSE WITHOUT PENALTY [6]. Thank you for your help.

Demographics:

1. Age:___________

2. Year of Birth: ________ Month of Birth: _________

3. Height: _______________

4. Weight: _______________

5. Gender:_______________ [4]

6. Current Employment:_____________________________

Vision:

7. A) Do you have:

Glaucoma . . . . .NO / YES
Cataract(s) . . . . NO / YES
Macular degeneration . . . . .NO / YES
Amblyopia/lazy eye/patch……………………………………….…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? ____

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

27. On average over the course of your lifetime, do you experience sensitivity to motion, motion sickness, and/or sensitivity to 3D movies/virtual reality? Please explain.

28. Have you ever ridden a train or subway?   NO / YES

If yes,,, How frequently did this occur in the past year?

Appendix C

Concussion/Healthy History Questionnaire

1. At what age did you begin playing organized sport? _________
2. How many years have you played? _______________________
3. How would you describe your style of play? – check one

☐ aggressive ☐ offensive defensive ☐

☐ finesse ☐ checker ☐ __________

4. Have you ever suffered from neck pain in the past? YES / NO
5. Are you currently experiencing neck pain? YES / NO
6. Have you ever suffered a concussion? YES / NO / UNSURE
7. If yes to #6,
   a. How many times while playing sport in the last 5 years? _______
   b. Please describe how your most recent concussion occurred

   ____

   ____

   ____

   c. How long did the symptoms last? Circle one

   1-3 days 4-7 days 8-10 days

   11-14 days more than 2 weeks more than 30 days
   d. What is the longest you have had to sit out because of a concussion? Circle one

   1-3 days 4-7 days 8-10 days

   11-14 days more than 2 weeks more than 30 days
   e. Who told you that you could not play because of the concussion? Circle one

   Myself Family Doctor team therapist

   Coach chiropractor other__________
   f. When did you become asymptomatic? _________________________ (date if possible)
8. Have you ever been hospitalized, knocked out, become unconscious, and or lost your memory due to a head injury? YES / NO
   a. Please describe____

9. Do you suffer from headaches? YES / NO
    a. How frequently? (circle one) Every day 1-2 times/week 1-2 times/month
    b. Where are your headaches located? ______________________________
    c. Have you had headaches for more than three months? YES / NO
       If yes, please explain______________________________
10. Do you have a history of migraine headaches? YES / NO
    a. How frequently?______________________________
    b. Please Describe ______________________________
    c. Do you take medications for migraines? ______________________________
11. After being hit in the head in sports, have you ever experienced any of the following symptoms:

☐ confusion ☐ getting 'dinged' ☐ headaches

☐ dizziness ☐ balance problems ☐ poor memory

☐ poor memory ☐ blurry vision ☐ nausea

☐ ringing in the ears ☐ ____________________

12. In regards to how you feel NOW, please rate the following:

	none	mild		moderate		severe	
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Trouble falling asleep (if applicable)	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6

13. Do the above symptoms get worse with physical activity? YES / NO

14. Do the above symptoms get worse with mental activity? YES / NO

Appendix D

WILFRID LAURIER UNIVERSITY INFORMED CONSENT STATEMENT
Persistence of visuomotor deficits in previously concussed, symptom-free individuals
Alyssa Prangley (pran5160@mylaurier.ca)

You are invited to participate in a research study. The purpose of this study is to investigate the extent to which one's behaviours are influenced by the amount of peripheral visual movement during a collision avoidance task. Upon consent to participate, you will be asked to participate in the testing. Your health is in no way compromised for this study. The study will be conducted by myself (Alyssa Prangley) as a graduate student and my supervisor, Dr. Michael Cinelli from the Department of Kinesiology and Physical Education at Wilfrid Laurier University.

INFORMATION

The participant will be asked to complete a series of walking tasks over flat ground within a virtual reality setting that will be administered by Alyssa Prangley. In addition, you will be asked to complete two questionnaires, a Risk Taking Behaviours questionnaire as well as a Health History Questionnaire. PARTICIPANTS WILL ALSO BE ASKED TO PARTAKE IN VISUAL TESTS TO ENSURE ADEQUATE VISION FOR THE VIRTUAL REALITY SETTING. PARTICIPANTS WHO ARE IDENTIFIED AS HAVING LESS THAN 20/40 VISION WILL BE EXCLUDED FROM THE STUDY.

RISKS

Participants may experience some of the following physical risks: disorientation, light-headedness, boredom, and potential motion sickness due to the nature of virtual reality. If necessary, participants will be allowed to take breaks at any point during the experiment. PARTICIPANTS WHO EXPERIENCE MOTION SICKNESS WHILE WEARING THE HEAD MOUNTED DISPLAY WILL BE EXEMPTED FROM PARTICIPATION. REST AND REFRESHMENTS WILL BE PROVIDED TO ALL PARTICIPANTS AS NEEDED. THESE SYMPTOMS WILL LIKELY RESOLVE SHORTLY AFTER REMOVING THE HEAD MOUNTED DISPLAY [20] Participants will be closely watched by the supervisors to ensure safe navigation through the space. If you feel that you are unable to continue the study, you are able to withdraw at any time.

BENEFITS

Although participants will experience possible disorientation and light-headedness, these reactions will subside upon removing the virtual reality head set and help findings will help to further the understanding of the role of vision in the recovery of concussion.

COMPENSATION

ALL PARTICIPANTS WILL BE COMPENSATED $10/HR FOR THEIR PARTICIPATION WITHIN THE STUDY AS FUNDED BY THE WILFRID LAURIER UNIVERSITY CATEGORY A – INTERNAL RESEARCH GRANT [20].

CONFIDENTIALITY

Each participant will be given a unique identification label that only the graduate student conducting the study and supervisor, Dr. M. Cinelli understand. Only the principal investigator and supervisor will have access to the research information. Participants will not be identified in presentations or journal articles as individuals but presented in group means.

FEEDBACK AND PUBLICATION
A summary of the findings from this study will be presented during a poster board presentation in the Science Atrium on Wilfrid Laurier University campus. The information and data collected from this study will be used for journal publications and upcoming conferences.

CONTACT
If you have questions at any time about the study or the procedures, (or you experience adverse effects as a result of participating in this study) you may contact the researcher Alyssa Prangley at (519) 851-4666, or supervisor Dr. Michael Cinelli at (519) 884-0710 x 4217. This project has been reviewed and approved by the University Research Ethics Board. 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, extension 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, and feel at any time that you are unable to continue with the study you may withdraw 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.

CONSENT
I have read and understand the above information. I have received a copy of this form. I agree to participate in this study.

Participant's signature____________________________________ Date _________________

Investigator's signature___________________________________