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An athletic approach to studying perception-action integration: Does sport-specific training, and the impact of injury, influence how individuals visually guide navigation?

Carmen Baker
Wilfrid Laurier University, bake7070@mylaurier.ca

Jennifer Campos Ph.D
Toronto Rehabilitation Institute, jennifer.campos@uhn.ca

Michael E. Cinelli Ph.D.
Wilfrid Laurier University

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Does sport-specific training, and the impact of injury, influence how individuals visually guide navigation?

by

Carmen Baker

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Abstract

The objective of this thesis was to investigate perception-action integration capabilities of individuals during a choice navigation task. This task assessed navigation strategies in open space while individuals avoided colliding with two vertical obstacles that created a body-scaled, horizontal gap, at three varying obstacle distances from the starting location (3m, 5m, 7m). The two studies completed in this thesis employed the same paradigm to assess the hypothesized group differences. Gaze behaviours and kinematics of navigation strategies were compared between: 1) athletes specifically trained in navigating in open space versus non-athletes; and 2) athletes with post-concussion syndrome (PCS) versus non-concussed, specifically trained athletes. Specifically trained athletes have been identified as demonstrating more successful perception-action integration in discrete motor tasks related to their sport (Mann et al., 2007; Vickers, 2007). However, whether these abilities translate to the continuous motor task of obstacle avoidance in open space was unknown. The purpose of Study 1 was to identify the influence of sport-specific training on navigating in open space (i.e. navigational strategies of large field sport athletes) compared to age-matched, non-athletes. It was hypothesized that specifically-trained athletes would demonstrate fewer, longer fixations, suggesting a more successful perception-action integration strategy (as defined by Mann et al., 2007), and would employ more sport-specific navigation strategies than non-athletes by maintaining their straight trajectory toward the goal (Fajen & Warren, 2003). Athletes were found to make fewer, longer fixations than non-athletes. However, no differences were observed between navigation strategies of the two groups, nor were any kinematic measures found to differ between groups. It can be concluded

that athletes and non-athletes differentially obtain visual information to perform the same actions, suggesting that athletes and non-athletes differentially perform perception-action integration when navigating in open space. Future studies are required to identify sport-specific nuances of navigation (moving obstacles, running) to better identify athletic-related navigation strategies.

Although athletic training can enhance perception-action integration strategies, sport-related injuries can hinder this process. Following a concussion, individuals experience deficits of perception-action integration that persist well beyond 30 days of recovery, post-concussion (Baker and Cinelli, 2014; Slobounov et al., 2006). These perception-action integration deficits may also exist in individual with postconcussion syndrome (PCS). The purpose of the Study 2 was to identify whether perception-action integration deficits persist with the persistent physical symptoms of concussion characteristic of PCS. The current study revealed that athletes with PCS did not differ from non-concussed athletes on any measure of visual fixation strategy, nor were they found to differ on any kinematic measure assessed. These findings suggest that in the context of the current paradigm, athletes with PCS have no perception-action integration deficit. In that, athletes with PCS may have adapted perception-action integration strategies to navigate with equal efficiency as a specifically-trained group of athletes or that the paradigm was not sensitive enough to identify these differences. Such findings suggest that more research is required to assess what, if any, perception-action integration deficits persist with persisting physical symptoms of PCS to better benefit rehabilitative procedures and outcomes for these individuals.

Together, these studies add to what was previously known about perception-action integration, as it relates to navigation. Both studies assessed perception-action integration in unique populations that add to understanding of behavioural dynamics in the sport setting. Study 1 builds on a line of research assessing affordance theory and behavioural dynamics in sport (Fajen, Riley, & Turvey, 2008). The findings of this study suggest that although navigation strategies did not differ between specifically trained athletes and non-athletes, visual search strategies employed in task did. Such findings add to the understanding that sport-specific training influences perception-action integration, through our understanding of how athletes obtain visual information to perform actions. This thesis did not identify perception-action integration deficits in athletes with PCS. These findings suggest that the individuals in the present study likely adapted to their injury as they demonstrated equal ability in gaze and navigation strategies to specifically-trained athletes. As such, further research is required to assess the cognitive, motor, and sensory-motor deficits that may persist with the persisting physical symptoms of PCS. As individuals with PCS do not demonstrate similar visuomotor integration deficits as individuals with acute concussions (Baker & Cinelli, 2014), such individuals must be assessed and researched as a separate population.

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Your work is going to fill a large part of your life, and the only way to be truly satisfied is to do what you believe is great work. And the only way to do great work is to love what you do.

- Steve Jobs

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Key Terms

Center of Mass (COM) – A weighted average of the whole body mass. This point exists in the absolute center of a weighted object, such that their 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 right and left shoulder are used to calculate a weighted average with a marker on the mid-back, to create a vertical projection of the individual's position in space.

Kinematic(s) – Term used to describe body movement. In this study the term kinematic(s) refers solely to the marker setup and the fact that it obtains data about participants' movement through the understanding of COM.

Dynamic Stability – The allosteric state of the body – the ability to maintain balance while moving. This can be measured by assessing medial-lateral COM sway, as more variable sway suggests poorer control of the body (Hackney & Cinelli, 2013).

Obstacle Avoidance – The process by which people do not collide with environmental objects; accomplished through adaptive locomotion.

Saccade – A saccade is defined as a rapid eye-movement that occurs when an individual switches their gaze from one object in the environment to another.

Fixation – As per Carpenter (1988), a fixation is defined as a stable gaze toward a single target for a minimum of 100ms. Within this definition, a fixation requires overt attention.

Critical Point – A change in environment that results in a change in action. For example, Hackney & Cinelli (2013) identified that the Critical Point of younger adults is 1.4 x SW, such that they tend to change their action strategies when avoiding gaps smaller than this, and walk straight through gaps equal to this size or greater.

1. Introduction

1.1 Theories of Perception-Action Integration

Affordance Theory was built on the concept that in order to act, one must perceive, but in order to perceive, one must act (Gibson, 1979). Perception action integration is a cyclical process. To perceive, individuals use their visual system to gain information about the environment. This allows for accurate and precise interactions with the environment, in other words, action. To act, individuals create forces and use dynamics to change their position with respect to the environment. In turn, this action changes the individual-environment relationship, and therefore affects how the environment is perceived (Figure 1.1).

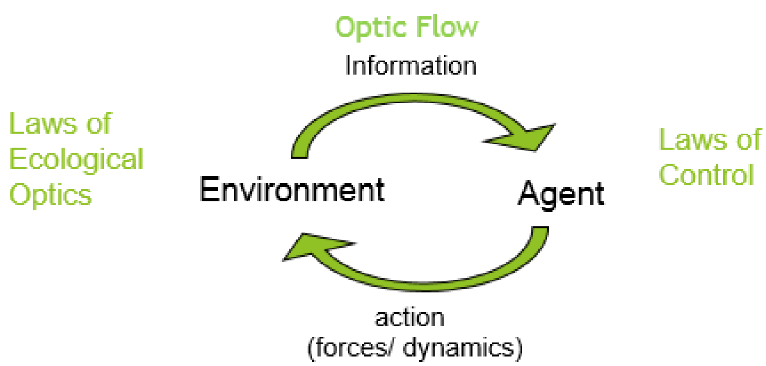

Figure 1.1. The relationship between perception and action is cyclical. The environment is visually perceived through the laws of ecological optics. Information is obtained by the agent through the visual system. The agent uses this information to perceive their action capabilities in the given environment. The agent acts on the environment through forces and dynamics (i.e., physical capabilities, stability). These actions alter the environment-agent relationship and influence perception.

Affordance Theory takes into account the particular features of the individual as well as the environmental characteristics associated with particular situations. The term affordance refers to the environmental possibilities for each individual (Gibson, 1979). Take for instance the example of a chair. The chair has unique properties: it has four legs, a straight back, and a horizontal platform. The individual also has unique properties: if they are an adult, the chair may be at an appropriate height to allow for sitting. In this scenario, based on the properties of the chair as well as the individual, the chair affords sitting. However, if the individual is a toddler, the chair may not be at the appropriate height for sitting, but may be designed in such a way that the toddler may climb it. As such, this individual-environment scenario affords climbing in toddlers. Affordance Theory thus defines the unique relationship between the individual and environment. Further, these factors are inherently related. It cannot be assumed that the perception of a chair is for sitting without understanding the aptitudes of the individual, nor decide the inherent properties of an environment without perceiving them. Thus, individuals must accurately perceive their own aptitudes as well as the properties of the environment to accurately perceive affordances (Gibson, 1979).

Inherent characteristics or experiences of individuals may influence their action capabilities (Fajen, 2013). For instance, specific training may enhance an athlete's physical dynamics when acting in an environment (Fajen, Riley, & Turvey, 2008). In contrast, injury may negatively affect individual dynamics (Baker and Cinelli, 2014). Unique characteristics of individuals influence their abilities to act within the environment. The individual must then understand their action capabilities and accurately perceive the environment for the actions they can perform within it. Additionally, athletic training may increase an individual's ability to integrate sensory information (i.e. vision for perception). Perhaps athletes are more adept at identifying important sensory cues that allow them to perform at high levels (Higuchi et al., 2011). Thus, the internal factors of 1) vision for perception and 2) dynamics influence the manner in which the environment is perceived, and in turn affect how an action is performed.

Within the tenets of affordance theory, intrinsic representation of the environment allows individuals to gauge their abilities through internal units of measurement (i.e., eye height or shoulder width). Through this method, the individual does not need to process visual information both internally and externally, but rather integrate environmental information and perceive these measures against their unchanging, intrinsic body-based measures (Warren, 1984). As most individuals' intrinsic measures are relatively constant, such as eye-height or shoulder width, they are able to consistently use such features to perceive their ability to interact with the environment (Fajen, 2013). The theory of intrinsic representation allows for more accurate perception for action in novel environments (Warren, 1984; Warren & Whang, 1987; Hackney & Cinelli, 2013).

Warren (1984) determined that when climbing stairs, individuals scale the perceived climb-ability of a stair through the intrinsic measure of their leg length. Further examination by Warren and Whang (1987) found that individuals used intrinsic information (shoulder width) to determine the pass-ability of a horizontal gap. It was found that regardless of whether observers were stationary or mobile, all participants' *perceptions* of whether they could safely pass through the aperture were rooted in body-scaled information. Thus, all observers were able to perceive the size of their widest point (shoulder width) to accurately judge whether they could safely pass between two obstacles (Warren & Whang, 1987). These findings have since been reported by numerous studies examining gap crossing strategies (Fajen, Diaz, & Cramer, 2011; Franchak, Celano, & Adolph, 2012; Hackney & Cinelli, 2013).

Aside from perceptions of action capabilities, Warren and Whang (1987) also found that participants used body-scaled information to *navigate* through an aperture. The authors recruited two groups of participants: those with shoulder widths narrower than the average male, and those with shoulder widths wider than the average male. Participants were asked to walk or run between two obstacles that created a horizontal gap. When they could not safely pass through the gap without changing their body dimensions, participants were asked to rotate their shoulders to fit through the aperture. Participants with wider shoulder widths were found to rotate their shoulders through more apertures than participants with narrow shoulders. However, when results were normalized to shoulder width, Warren and Whang (1987) found that all participants began rotating their shoulder (i.e., Critical Point, π_c) at the same ratio of aperture width (A) to shoulder width (S). In that, regardless of how wide the participants' shoulders were, all participants began rotating their shoulders through apertures that were less than 1.3 times their shoulder width (i.e., A/S=1.3). These results have been replicated throughout the literature (Fajen, Diaz, & Cramer, 2011; Franchak, Celano, & Adoph, 2012; Hackney & Cinelli, 2013; Hackney, Zakoor, & Cinelli, 2014; Higuchi et al., 2011). As such, all of these authors found supporting evidence for Gibson's Affordance Theory such that all participants used intrinsic information about their physical constraints, in this case shoulder width, to guide their perceptions of the environment to perform accurate movement strategies within said environment.

Although Affordance Theory determines possibilities for action within an environment, it does not fully explain goal directed movement relative to task instructions or outcomes. To take this concept further, one must also consider the expected and resultant outcomes of the movement. What is the desired goal or behaviour? Behavioural dynamics adds a caveat to Affordance Theory by also imposing task constraints into the given individual-environment system. With given task constraints, individuals must also perceive certain environmental features as attractors (i.e. task requires someone to walk to a goal) or otherwise (Fajen & Warren, 2003). Through behavioural dynamics, a more holistic understanding of adaptive behaviour or adaptive locomotion emerges. This theory explains how individuals exploit the informational (sensory perception) and physical (environmental and biomechanical) constraints of the *given task* to create stable strategies (Warren, 2006). Indeed, when the findings of Warren and Whang (1987) are re-considered under the caveats of behavioural dynamics, the authors' findings are relative to the experimental instructions. Participants were required to reach a goal by passing obstacles, and had to do so by navigating through the gap. Therefore, the interaction with both the obstacles and the goal had to be considered by the participants, as well as the task instructions (rotate shoulders, and not squeeze, or change travel path) (Fajen & Warren, 2003). From this new definition, we may better understand why unique action strategies are observed in scenarios that afford highly similar actions through an understanding of task constraints including experimental instruction.

Of all the sensory systems used to provide perception for action, why did Gibson, Warren, and other researchers focus on vision? One main property of vision is that it is the most vital sensory system to provide individuals with rich information at a distance (exteroception) (Patla, 1997). As such, understanding how individuals use vision to guide actions is vital to understanding how collisions with obstacles are avoided. More specifically, individuals are incredibly adept at avoiding collisions with obstacles including telephone poles, other people, and doorways. Individuals generally move toward areas of open space that afford safe travel and avoid obstacles and areas that do not afford safe travel (Fajen & Warren, 2003; Gibson, 1979). To do so, individuals need to assess the size of these gaps at a distance and use a sense that can provide information about the size of the gap relative to their body size (exproprioception) (Patla, 1997). To better understand Affordance Theory and behavioural dynamics, one must understand how visual cues are used to guide the perception of safe navigation. In the following section, literature is reviewed for humans' use of vision for adaptive locomotion.

1.2 – Visual Cues

1.2.1 Binocular Vision

The eyes of human beings have evolved to be located on the front of the head in order to allow for better depth perception (Gibson, 1979). Fusional vergence movements exist to decrease binocular disparity to allow images to lie on the same point on the retina of both eyes. Eyes thus move in opposing directions to allow the image to fall more symmetrically on the foveae of both eyes (Tresilian, 2012). This is referred to as disconjugate eye movements (Heitger et al., 2009). Objects in near-space tend to require convergence of the eyes: both eyes rotate toward the midline of the body (which results in two very different images on the retinas). Objects in far-space tend to cause divergence: the eyes rotate away from the midline of the body to create similar images

(Tresilian, 2012; Vickers, 2009). Therefore, the amount of convergence of the eyes can identify depth-cues to determine the distance at which the environment object lies. When the observer or object moves in space, vergence pursuit allows the object to remain foveated (Vickers, 2007). This allows for continual perception of the depth of this object. Again, the observer can determine whether the object is moving closer or further in depth and at what rate based on how rapidly the eyes are converging or diverging on the object (Tresilian, 2012).

1.3 – Vision for Adaptive Locomotion

Adaptive locomotion can be defined as the ability to ambulate through complex environments (Higuchi, 2013). This is performed through adjusting gait strategies to avoid obstacles in near or far space. Although multiple sensory cues are required for locomotion, vision is the only system that provides information at a distance (Patla, 1997). As such, vision is integral to adaptive locomotion to enable anticipatory and on-line control. In static environments individuals can adapt a pre-planned, anticipatory strategy, and create an avoidance strategy *a priori*. However, in more challenging environments, participants may adopt a reactive strategy, in which they use on-line visual cues to guide locomotion on an as-needs basis (Higuchi, 2013). Typically researchers assess the use of these strategies through analysis of gaze strategies. Individuals who use vision to guide their current stepping strategy, through visual fixations in near-space, are adopting an on-line visual strategy (Chapman & Hollands, 2006a). It has been shown that these fixation strategies are typically only adopted when participants are tasked with creating very accurate navigational strategies (i.e. stone stepping tasks) (Chapman and

Hollands, 2006a, b). In all other studies reviewed, participants have been found to look ahead at a goal, with gaze fixations occurring toward far-space. This strategy has been attributed to participants looking where they are going (Bernardin et al., 2012; Cinelli, Patla, & Allard, 2009; Higuchi, 2013; Hollands, Patla & Vickers, 2002). However, Patla and Greig (2006) found that on-line visual control is required to accurately step over obstacles. This finding has been partially attributed to the necessity of having very accurate footfall locations and of placing the trailing foot in the appropriate location in front of the obstacle (Patla & Greig, 2006), but on-line control is required for aspects of novel, unpredictable environments (Cinelli et al., 2009). Within these challenging situations, participants assess the environment to create an action strategy and will fixate the goal in the final stages of approaching the obstacles (Cinelli et al., 2009). To summarize, participants have been found to fixate the goal in the end-stages of navigation, using anticipatory visual control to more efficiently avoid predictable obstacles (Cinelli et al., 2009; Higuchi et al, 2009; Higuchi, 2013). With this in mind, optic flow and binocular disparity are likely key contributors to accurate steering. As participants tend to use a look-ahead strategy toward the goal, regardless of obstacle condition, the goal becomes the FOE (Higuchi, 2013); look-ahead strategies will enable participants to gauge walking speed, heading direction, and time to collision.

1.4 - Visual Perception for Gap Crossing

The concept of using body-scaled information to guide action has been evidenced in gap crossing (Warren and Wang, 1987; Hackney and Cinelli, 2013; Higuchi et al., 2006). However, there are several possibilities for *how* individuals use perception of body-scaled information to guide actions. Computationally, individuals can perceive the width of an aperture relative to their body size by using the intrinsic measure of eye height (Fajen, Diaz, & Cramer, 2011). The reason that eye height can be used is because shoulder width is a constant proportion of standing eye height. As such, a gap can be perceived as passable based on one's knowledge of this eye height to shoulder width ratio (Fajen, 2013). It has been found that this concept of perception for safe navigation through an aperture is equally accurate when the individual is stationary and while in motion (Warren & Whang, 1987). Therefore, the concept of perceiving the relationship between one's body size and the environment through eye-height can also be used to determine action capabilities for any given aperture width in dynamic scenarios as well (Fath and Fajen, 2011). Other body-scaled dynamic measures of aperture width include stride-length scaled information and head-sway information (Fath and Fajen, 2011). Both are used to calibrate aperture width in terms of shoulder-width. Fath and Fajen (2011) isolated each of these possible sources of information and determined that individuals use all three measures to perceive safe aperture crossing. They concluded that perception-action integration is achieved through the use of accurately acquiring multiple visual cues and accurately assimilating them for action (Fath & Fajen, 2011).

Although the literature emphasizes visual contributions to adaptive locomotion, this sensory system does not work in isolation. Campos and her colleagues (2012 & 2013) determined the contributions of vision and body-based sensory systems (vestibular, kinesthetic and proprioceptive) in the perception of travelled distance. In the first experiment (Campos et al., 2012), healthy young participants actively walked or were passively moved (in a wheelchair) while visual gain was manipulated using a head mounted display. Participants were asked to judge the distance they had traveled under conditions of congruent visual and body based cues, or incongruent with visual gain manipulations of 0.7 and 1.4. It was found that participants tend to weigh body-based sensory information higher than visual information to perceive distance travelled. In the later study (Campos et al, 2013), similar methodologies were employed using a treadmill in a virtual reality environment. Through this, linear acceleration (via otolith receptors of vestibular system) information was eliminated, and the gain of kinematic and visual information could be manipulated. In this second experiment, the gain of vision and kinesthetic information were individually manipulated through independently manipulating the rate of optic flow or speed of the treadmill. It was again found that under both types of gain conditions body-based sensory information was weighted higher than visual information when perceiving distance. However, when the gain of proprioceptive information was altered (increase treadmill speed in absence of change of gain in optic flow), participants tended to reduce the weight of body-based sensory information for distance perception (even though it was still weighted higher than vision). Therefore, sensory systems are used in conjunction to allow participants to accurately perceive their movements within the environment.

Taking these findings in combination with previously presented work, it can be understood that younger adults tend to weigh body-based cues along with visual cues when integrating perception for action. Specifically, this concept has been identified as a key facet of Affordance Theory and behavioural dynamics as younger adult participants use body-based information to visually guide action strategies (Hackney & Cinelli, 2013). Healthy young adults integrate multi-sensory information to accurately perceive their body and its capabilities for actions in the environment.

1.5 - Athletes

A key facet of Affordance Theory is the importance of perception for action, as well as the importance of action for perception. Successful athletes are those who effectively and reliably use perception to achieve motor related goals. These concepts were articulated by Fajen, Riley, and Turvey (2009) in an article that called for the pairing of affordances and athletes. The authors suggest that with respect to affordances, athletes have an increased ability to use body- and action-scaled perceptual judgements to efficiently interact with their environment. In particular, the authors argue that athletes must have specifically trained visual search strategies, through which athletes are able to extract important visual information more effectively than non-athletes in environments related to their sport training. That is to say, athletes more accurately choose salient information from the visual array than non-athletes due to their sport-specific training (Fajen, Riley, & Turvey, 2008).

1.5.1- Athletic Related Gaze Strategies

Numerous studies have found that elite athletes tend to make fewer, longer fixations than their novice counterparts when performing a task relevant to their sport (Dalton, 2012; Goulet, Bard, & Fleury, 1989; Ripoll et al., 1999; Savelsbergh et al., 2002; Vickers, 2007). These studies concluded that fewer, longer fixations are indicative of a more effective visual search strategy as such fixation strategies were found to correlate with more successful sporting outcomes (Mann et al., 2007; Vickers, 2007). Typically this results from the method in which authors define as a ‘fixation’; a fixation (gaze being directed toward an object in space) of a minimum of 100ms is typically used, and is deemed the required amount of time for conscious attention (Carpenter, 1988). Therefore, if athletes are able to pay attention to fewer, important environmental features, and do so for longer, they draw salient information from the environment more effectively from these environmental features. All of the above mentioned studies have concluded that because athletes are more effectively attaining salient visual information, they are able to create more successful action outputs, leading to elite sporting outcomes.

However, the sequencing of visual fixations does not appear to affect success rate or skill-level in sport. In a review of literature, Land (2006) suggested that stereotypical sequences of eye movements accompany every task, but that individual differences exist between these sequences. Such variability was noted by Williams and colleagues (1994) who identified both intra- and inter-group variability on sequencing of eye movements between expert and inexperienced soccer players. Conversely, in a similar study, authors found both expert and skilled participants looked at salient cues in similar patterns, where un-skilled participants performed different sequences that included non-relevant cues (Williams, Singer, & Frehlich, 2002). Fixation sequencing was not found to be an important feature of perception-action integration in complex, gap-crossing environments. Cinelli, Patla, and Allard (2009) noted that fixation sequencing did not differ, regardless of the complexity of the task. Their study observed fixation patterns of younger adults, attempting to safely navigate through a moving gap, where two doors either moved symmetrically (less-complex) and asymmetrically (more-complex). The authors found that although participants made longer fixations under the more-complex condition, the sequence of environmental objects that participants fixated were similar between the two conditions (Cinelli, Patla, & Allard, 2009). Further, all aforementioned studies found that all participants, regardless of skill-level, tended to fixate the salient features of the task. Therefore, it can be concluded that the sequence of fixations does not differ between skill-levels, nor does this outcome provide unique information on how participants performed a gap-crossing task.

Through an extensive line of research, Vickers and her colleagues have identified how athletes use vision for action. In particular, Vickers' work focuses on visual fixations at the end-state of an action, or final fixations, to determine where athletes tend to look in the final stages of a movement. For example, in basketball free throws, Vickers observed that specifically trained athletes tended to have fewer, longer final fixations than novice athletes (Vickers, 1996). Specifically, these athletes tended to fixate the backboard to gain information about this location when shooting. Athletes who had fewer and longer final fixations of the backboard were found to have more accurate free-throw shots than those with shorter-duration final fixations. Expert free-throw shooters tended to look longer at relevant areas for action than non-experts at the final stages of an action. Vickers coined this term the 'Quiet Eye', and has found that it exists in numerous other athletic endeavours including, but not limited to, putting, dart throwing, and ice hockey goaltending and defending tactics (Vickers, 2004; Vickers, Rodrigues, & Edworthy, 2000; Panchuk & Vickers, 2006; Martell & Vickers, 2004). In all studied athletes, Vickers and her colleagues noted that the Quiet Eye and accompanying fewer, longer visual fixations throughout the duration of the sporting activity allowed specifically trained athletes to perform sport-specific action strategies more successfully. Therefore, it can be concluded that specifically trained athletes not only have successful action strategies (as observed by their consistently high performance), but also have effective visual search strategies to create such actions.

Practice has been found to increase the likelihood that individuals create more successful action strategies while engaging in a visual search strategy with fewer, longer fixations; such a relationship has been found to be highly context-specific (Kelley & Yantis, 2009; Yantis & Egith, 1999). This is the principle behind the pairing of Quiet Eye and successful motor strategies in sport. Vickers (2009) discussed the concept of Quiet Eye as it relates to behavioural dynamics. It was suggested that to visually perceive for action, an individual becomes increasingly more skilled by identifying direct optical relationships from the environment. By this, Vickers (2009) suggests that Quiet Eye develops as an optical skill. This is because Quiet Eye optimizes attention to salient visual cues including optic flow and orientation in the environment and to task constraints (Vickers, 2009). From this, it can be concluded that context-specific training increases the ability to use Quiet Eye, which decreases the necessity for individuals to overtly attend to more numerous environmental features as this single fixation point provides information about both the task and environment, without having to overtly shift attention and gaze.

However, Vickers' work does not extend this concept beyond discrete sporting movements. Opportunities for action in sport, and thus affordances, often exist in dynamic situations. As such, gaps that afford passage may only exist for a few seconds, and then close quickly to create an impenetrable wall of defense. Therefore, it is important to identify how athletes differ in their perception of other movements for action. Such a study was conducted by Higuchi and colleagues in 2011. The authors examined the difference between rugby players, American football players, and non-contact athletes when moving through a horizontal gap. Participants were asked to walk and run, *constrained* through gaps scaled to proportions of shoulder width. No differences were observed between the action strategies of groups of individuals in the walking condition. However, when asked to run through the gaps, American football athletes were found to produce significantly smaller shoulder rotation magnitudes than the other athletes. This finding suggests that specifically-trained athletes were better able maintain their trajectory, optimizing their movement through the environment (Fajen & Warren, 2003). It can be concluded an athlete-associated advantage does not exist. Being a skilled athlete did not directly transfer to the gap crossing task. Instead, the specific characteristics of the practiced skills influence performance in the paradigm. This conclusion may explain why rugby and American football athletes did not react to the paradigm similarly. Perhaps the sport specific nuances of American football and rugby can assist in this explanation. American football athletes are used to being forced to complete a particular movement under severe movement constraints. For example receivers must run a particular route, or running backs must run through a given gap created by their offensive line. However, in rugby, athletes are granted more freedom with their movement strategies. On any given play, rugby athletes may perceive a gap opening along any point down the defensive line. Unlike football athletes, rugby athletes are encouraged to adapt their play to find this particular space. Thus, it is likely that athletes who are trained to look for space, as opposed to forcing their way through a specified gap, would react differently in an gap crossing task.

1.6 Rationale for Study 1

Regardless of sport, it can be understood through previous work that athletes with specific training have better perception for action to perform trained skills (Vickers, 2007). As Fajen and his colleagues stated, “We believe the affordance concept is ripe for application in sport” (2009, p.87). This is a result of athletes better perceiving their action capabilities, and, as many authors have stated, may be a reflection of specifically trained perceptual abilities (Fajen et al, 2009; Vickers, 2007). Therefore, given an *unconstrained* gap crossing task (as compared to Higuchi & colleagues, 2011 *confined* gap crossing task), that may be applicable to field sport athletic training, one would expect to find athletic related differences in perception-action integration. As previously mentioned, athletic related differences in gap crossing appears to be highly context-specific (Higuchi et al., 2011). Because of this, it has been concluded that the differential training between rugby and football athletes may have resulted in the differences in navigation strategies observed in the study conducted by Higuchi and colleagues (2011). In the current study, it was important to identify a group of athletes with homogenous training in obstacle avoidance. Athletes were recruited from large field sports (rugby, field hockey, soccer, and lacrosse) where athletes are specifically trained to move to open space.

In addition to attempting to assess a more homogenous group of athletes, the current study aimed to assess how unique environmental factors influence action strategies. Fajen and Warren (2003) identified that young adults’ path selection is determined by relative distance from the obstacle. These authors found behavioural dynamics were specific to both the obstacle's distance from the starting location and the obstacle's proximity to the goal. Participants were found to deviate less from a straight walking trajectory when navigating around an obstacle located further from the start, and closer to the goal compared to other obstacle conditions (Fajen & Warren, 2003). Fajen & Warren (2003) concluded that this was likely a result of the inherent properties of the goal-obstacle interaction. When the obstacle was located further from the goal, participants were able to break up the task to first avoid the obstacle and then reach the goal. When the obstacle and goal were in close proximity, participants changed their action strategies to more efficiently walk to the goal while concurrently avoiding the obstacle in this condition (Fajen & Warren, 2003). In multiple obstacle avoidance, Hackney, Vallis, and Cinelli (2013) suggest that the actions of young adults are based on body-scaled information and that visual perception helps guide actions. Numerous studies have identified that path selection around or through a gap is based on body-scaled information (Hackney & Cinelli, 2013; Higuchi, Cinelli, & Patla, 2009; Higuchi et al., 2011). However, these action strategies have been found in the presence of a single obstacle distance. One unknown factor that may be contributing to path selection in multiple obstacle avoidance is the effect of multiple obstacle distances. Therefore, we hypothesize that in the current study neither the distance to the obstacles, nor the gap between the obstacles will uniquely determine route selection, but that the impact of both will interact to create differential action strategies. The relative contributions of these two factors on path selection may also be affected by differences in perceptual control between athletes and non-athletes. The majority of goal-directed locomotion research has examined the actions of healthy young adults, however it is also very important to understand the effects of athletic training, specifically those trained to avoid collisions, on actions and gaze behaviours. Observing the perception-action integration strategies of specifically trained athletes may reveal nuances in the perception-action system related to the nature of their sport specific training.

1.7 Rationale for Study 2

Concussion has been defined as a complex, pathophysiological process affecting the brain, induced by traumatic biomechanical forces (Cantu, 1996). The recovery and diagnosis of typical concussion cases has been well documented throughout the literature. Such injuries are suggested to resolve in a few weeks post-injury (McCrory et al., 2013). This conclusion is based on physical symptom recovery, which is assessed based on self-report. Physical symptoms of concussion are those that are perceived, such that their measurement can only be identified via self-report (for example: headache, feeling in a fog, irritability, pressure in head, fatigue; see Appendix C for full list). Physical symptoms of concussion are the current gold-standard diagnostic and recovery tool used to assess this injury (McCrory et al., 2013). However, studies have suggested that physical symptom recovery does not correlate with cognitive and balance recovery from concussion (Broglio et al., 2007; Broglio, 2015). A previous study found that cognitive and balance deficits persisted in a significant cohort of previously concussed participants, suggesting that both neurocognitive testing and balance assessments were a far better measure of concussion recovery than physical symptom report (Broglio et al., 2007). More recently, perception-action integration (visuomotor) deficits of concussion have been evidenced as an excellent measure of persistence of concussion (Baker & Cinelli, 2014; Locklin et al., 2010); such that deficits of acute concussion have been found to persist with a much longer timeline using these measures. Within this, visual control of navigation has been evidenced as a tool that may be particularly useful to identify recovery from concussion.

Far less is understood about the syndrome associated with persistent physical symptoms of concussion. There appears to be a significant gap in the literature concerning balance and perception-action integration deficits associated with post-concussion syndrome (PCS). PCS has been defined as retaining at least three of the following symptoms of concussion: headaches, dizziness, fatigue, sleep disturbances, emotional changes, attentional issues, and memory problems for two months (the DSM-5 suggests a three month minimum, whereas other sources suggest symptom persistence beyond the typical recovery period of 7-14 days). PCS is often associated with emotional and mood disturbances including anxiety and depressive symptoms (Broshek, 2015; McCrory et al., 2013; American Psychiatric Society, DSM-5). It is clear that individuals with PCS have a diffuse neurological injury, so it is perplexing as to why so little has been reported regarding the cognitive, balance, or visuomotor deficits of PCS. It is important to understand whether other features of acute concussion are also prevalent in individuals with PCS.

1.7.1 Stability Deficits of Concussion

Powers, Kalmar, & Cinelli (2013a, b) identified that previously concussed athletes demonstrate balance deficits in the absence of physical symptoms of concussion when they had been cleared to return to play. The authors noted that this was a result of the velocity of the center of mass movement, concluding that deficits were a result of dysfunction in higher-order integrative processes (Powers, Kalmar & Cinelli, 2013a).

In a dynamic stability paradigm, these authors identified increased swing-time variability during gait, suggesting an increased risk of falls in previously concussed football athletes through a top-down neurological impairment when these athletes were cleared to return to play (2013b). These authors also identified more conservative gait strategies during the acute phase of recovery, suggesting that recently concussed athletes decrease their center of mass (COM) movement to reduce destabilization moments while walking. Similarly, when assessing balance deficits, Catena and colleagues (2009) found that previously concussed individuals demonstrated more cautious gait strategies (decreased velocity, reduced medial-lateral sway) during unobstructed walking. Parker and colleagues (2007) also found similar COM control up to 14 days post-concussion in their cohort of previously concussed individuals. However, when a dual-task was employed, previously concussed athletes demonstrated more variable COM control up to 30 days post-concussion (Parker, Osternig, van Donkelaar, & Chou, 2007). These findings suggest that previously concussed athletes assign a significant amount of attention to maintaining dynamic stability. When this attention is divided, as in a dual-task, previously concussed individuals are found to have vastly more variable COM control, indicating poorer control of dynamic stability. Dynamic stability deficits have been identified in a cohort of previously concussed individuals up to 6 years post-injury (Martini et al., 2011). These authors identified slower gait and greater time in double support when individuals were required to perform a number of different dual tasks while walking.

1.7.2 Visual Deficits of Concussion

Primary visual impairment has been identified in recently concussed individuals (Galetta et al., 2015; Maruta & Ghajar, 2014; Ventura et al., 2015). These authors have identified abnormalities in saccades (speed and ability to attain fixation point), convergence, and accommodation. Increased gaze position error was identified by Maruta & Ghajar (2014), which they attributed to attention deficits. Similar findings were reported by Samandani and colleagues (2015), who correlated SCAT3 symptom reports with level of disconjugate eye movements. Disconjugate eye movements refer to convergence and divergence of the eyes; as individuals track an object moving closer to or further from them, their eyes move in different directions to enable continuous fixation of the object on both retinas (Tresilian, 2012). The authors concluded observing the level of inefficient disconjugate eye movements was an accurate, non-invasive assessment of concussion as disconjugate eye movements were highly correlated with physical symptom report (Smanadani et al., 2015).

Numerous authors have identified the usefulness of the King-Devick (K-D) test in assessing concussion. The K-D test assesses response time and accuracy of a task that requires individuals to fixate single digit numbers sequentially. These numbers are displayed on a card (or tablet screen) in discrete locations, requiring the individual to saccade efficiently to each target. Increased response time is indicative of less efficient saccades, suggesting a concussion. Studies have found that this score correlates highly with neurological sideline tests (i.e. SCAT3) to identify concussion in a variety of ages and athletic arenas (Galetta et al., 2011a, b; King, Clark, & Gissane, 2012; Leong et al., 2014; Ventura et al., 2015). However, in reviewing the literature, no research has evidenced the recovery of visual function with concussion recovery.

A single study has assessed visual function in post-concussion syndrome (PCS). Heitger and colleagues (2009) found poor visual motor function in a group of individuals with PCS. These individuals demonstrated a greater number of saccades, poorer eye movement timing, and visuospatial accuracy compared to non-concussed controls. These impairments were identified irrespective of the persistence of cognitive deficits in individuals with PCS. In his Master's Thesis, Sanders (2012) identifies that visual motor impairments abate with physical symptoms of concussion. Similarly, Thiagrajan & Ciuffreda (2014) conclude that oculomotor training assists the recovery process for previously concussed individuals still suffering from physical symptoms. These findings all appear to corroborate the fact that oculomotor deficits of concussion may only persist with persisting physical symptoms. Yet, these findings must be considered with caution, as it has been previously documented that physical recovery of concussion is not an accurate measure of absolute recovery from concussion (Broglio et al., 2007). Further, as there are almost no studies evidencing the persistence of visual motor deficits of concussion (Broglio et al., 2015), it is difficult to confidently conclude this relationship.

1.7.3 Visuomotor Integration Deficits of Concussion

Several studies have evidenced visuomotor deficits of concussion. Each study presented sequentially evidences visuomotor deficits of concussion over a prolonged timeline, such that with increased task complexity, visuomotor deficits are observed over a longer recovery time post-concussion. These results suggest that complex visuomotor tasks are able to identify deficits of concussion over a longer time-period than previously identified by simple cognitive and balance tasks (Baker & Cinelli, 2014; Locklin et al., 2010; Slobounov, Slobounov, & Newell, 2006). With respect to sport, Locklin and colleagues (2010) suggest the pairing of visuomotor tasks and dynamic balance to assess game-like perception-action integration will allow for more accurate assessment of return to play.

In their study, Slobounov, Slobounov, and Newell (2006) employed the moving room paradigm (see above; Lee and Lishman, 1975). The authors assessed the coherence between the oscillation of the room and body-sway in previously concussed individuals 3, 10, and 30 days post-injury. The authors found that coherence was significantly reduced at day 10 post-concussion, and that sway coherence had not recovered to baseline at 30 days. The authors concluded that visuomotor dysfunction persisted in their participants at least 30 days post-concussion (Slobounov, Slobounov, & Newell, 2006). Similar findings were presented by Fait et al. (2013) who assessed the navigation strategies of athletes who had sustained a concussion >30 days prior to testing, who had no physical symptoms and normal results on a neuropsychological examination. Previously concussed athletes tended to leave a greater safety margin (personal space) between themselves and the obstacle compared to uninjured controls. Further, these individuals also had poorer response accuracy to a cognitive dual-task. The authors conclude that previously concussed athletes who had been cleared for return to sport were demonstrating deficits in visuomotor processing and executive functioning.

Locklin and colleagues (2010) employed the Fitts' tapping task to assess visuomotor integration in a cohort of previously concussed individuals. The Fitts' tapping task is designed in such a way that as task difficulty increases, participants are required to reduce their movement speed in order to maintain target tapping accuracy. Task difficulty increases as the distance between targets increase and the size of targets decrease, requiring integration of vision and action for more precise movements (Fitts and Peterson, 1964). Athletes who had sustained a concussion in the previous year demonstrated slower movement time compared to control populations (athletes and non-athletes). These findings, however, were not statistically significant. The authors suggested that previously concussed athletes demonstrate visuomotor deficits within a year of injury, but a more complex task is required to obtain significant findings.

Baker & Cinelli (2014) employed a more complex, choice navigation paradigm, which assessed visuomotor integration and dynamic stability. Results identified that their cohort of previously concussed individuals who had been cleared to return to sport (30-110 days post-concussion), demonstrated more variable decision making for navigation than non-concussed counterparts. Further, these participants were also found to have more variable center of mass control, suggesting both visuomotor and dynamic stability deficits (Baker & Cinelli, 2014).

Together, these studies identify visuomotor deficits of concussion that persist well beyond 30 days of recovery. All studies suggested that regardless of physical symptom recovery, or baseline neuropsychological outcomes, visuomotor deficits were persistent and present in athletes who had been cleared for return to play. Therefore, visuomotor integration appears to be an important indicator of deficits of concussion, and should continue to be assessed and described in this population.

The literature on concussions and visuomotor control has repeatedly suggested that the length of recovery from acute concussion is much longer than initially understood. Such research has found that individuals with acute concussion make variable, inaccurate action strategies compared to their uninjured counterparts (Baker & Cinelli, 2014). In the athletic population, these findings are particularly important for reducing the rate of re-injury from returning to play too soon. Yet, although a significant portion of athletic-related concussions result in PCS (McCrory et al., 2013), very little research has been identified on this topic. Therefore, the purpose of the current study was to assess whether athletes with PCS demonstrate persisting visuomotor deficits in addition to persisting physical symptoms of concussion. If such deficits do persist, the findings of this study will help to inform rehabilitative practices for individuals with PCS. If the findings of this study do not find evidence of persistent visuomotor deficits, these findings can inform whether individuals with PCS may return to differing levels of activity including, but certainly not limited to, light physical activity and/ or the sport settings.

1.8 – Purpose and Objectives

The objective of this thesis was to investigate perception-action integration in multiple populations through employing a choice navigation task. Both studies employed the same protocol as it was the best method to assess the expected group differences. Gaze strategies and kinematics of navigation strategies were compared between athletes and non-athletes to quantify athletic-related differences in perception-action integration. It was hypothesized that athletes would demonstrate a more successful visual fixation strategy (as defined by Mann et al., 2007), and would employ sport-specific navigation strategies, through more efficiently navigating to the goal (as described by Fajen & Warren, 2003) compared to non-athletes. The same metrics were employed to quantify the deficits in perception-action integration in athletes who have been diagnosed with PCS. Athletes with PCS were compared to their uninjured, athletic counterparts to isolate the factor of PCS. With the previous hypotheses in mind, it was integral to compare athletes with PCS to other athletes to identify differences attributable to PCS only, as opposed to other, athletic-related factors. For the duration of this document, athletes and non-athletes will be examined and discussed separately from the comparison of athletes with PCS to non-concussed athletes.

Study 1: The purpose of this study was to determine if athletic related training influenced perception-action integration strategies in an unconfined gap-crossing task. This study aimed to assess the perceptual judgements, actions, and gaze behaviours of athletes as compared to non-athletes when avoiding two obstacles in open space.

Study 2: The purpose of this study was to identify whether visuomotor integration deficits persist with persistent concussive symptoms in a cohort of athletes with post-concussion syndrome (PCS).

2. Methods

2.1 - Participants

Healthy athlete and non-athlete participants were recruited through advertisements placed around the Waterloo Campus of Wilfrid Laurier University and by word of mouth. All participants were female, age 18-25. Females were recruited to ensure that the open-space in the experimental setup was greater than the gap created by the two obstacles. It was noted by Hackney, Zakoor, and Cinelli (2014, unpublished observation) that several of their male athlete participants had very large shoulder widths (i.e. greater than 70cm). This study was designed to ensure that the space on the lateral aspects of the obstacles was always much greater than the space between the obstacles (gap) to ensure that navigation always occurred in open space. To do so, study participants were sampled from the female population, who tend to have much smaller shoulder widths than males (particularly when recruiting athletes). The greatest shoulder width recorded for this study was 52cm (making the largest gap width 88.4cm, with open space on either side of the obstacles 255.8cm).

Participants were identified as non-athletes (N=12), athletes (N=12), or athletes with PCS (N=10) (see Appendix A for inclusion/ exclusion criteria); specific participant demographics are listed in Tables 2.1-2.3. The non-athletes identified themselves as having not participated in competitive sport currently or in the previous five years, nor had they ever reported competing in a large field sport (Table 2.1). Competitive sport was defined as any level of competition above recreational play. Participation in dance, at any level, was considered an exclusion criterion for all three experimental groups as dancers have been identified as having unique visuo-spatial abilities (Cortese, and Rossi-Arnaud, 2010). Female participants were also recruited from large field sports teams (soccer, rugby, lacrosse, and field hockey). These individuals were included if they identified as specifically-trained, reporting that they had over 250 hours of competitive sport experience in the previous two years (includes practice and game time, Table 2.2).

A third experimental group with PCS was recruited through Wilfrid Laurier University athletic therapists, and through sports medicine clinics in the Kitchener-Waterloo area (Appendix A). Female participants were included if they had been diagnosed with post-concussion syndrome (PCS) by a healthcare practitioner (doctor or neuropsychologist) and who had suffered physical symptoms of concussion for a minimum of 2 months prior to study participation. All participants in this experimental group were cleared to perform activities of daily living by their doctor, and were comfortable in the conditions required of the laboratory environment. Participants in this group had all participated in athletics at a comparably competitive level to the athlete group prior to sustaining their concussion. Eight participants in this study sustained their concussion from a sport-related activity. Two participants in this group sustained their concussion via a car accident, but had been participating in competitive sport at the time of the accident (Table 2.3).

	Age (years)	SCAT 2 Score	Number of Symptoms	Time Since Concussion	Sport	Level	Hours Played (Total)	Risk Taking Score	SW (cm)
1*	23	2	2	-	Volleyball	Rec.♦	-	95	43
2	21	0	0	>3 years	-	-	-	110	44
3*	23	8	4	-	Swimming	Club	-	98	50
4*	20	0	0	-	-	-	-	116	39
5*	22	25	12	-	Volleyball	Rec.	-	109	47
6*	21	3	3	-	Volleyball	Rec.	-	109	40
7	21	3	3	>3 years	Volleyball	Rec.	-	115	40
8	20	0	0	-	Running	Rec.	-	109	40
9	24	0	0	-	-	-	-	99	38
10	19	0	0	-	-	-	-	96	38
11	22	2	2	-	-	-	-	79	46
12	20	9	6	-	Swimming	Club	-	-	44
AVG	21.3±1.5	4.3±7.2	2.7±3.5					103.2±10.9	42.4±3.9

*Table 2.1: Demographics of non-athlete participants. * Denotes data was obtained for gaze strategies. ♦Rec. denotes any recreational play (i.e. house league, pick-up)*

	Age (years)	SCAT 2 Score	Number of Symptoms	Time Since Concussion	Sport	Level	Hours Played (Total)	Risk Taking Score	SW (cm)
1	22	0	0	-	Lacrosse	Varsity	600	92	44
2	23	3	3	>2 years	Lacrosse	Varsity	766	80	42
3*	19	8	3	-	Lacrosse	Varsity	369	122	44
4*	23	0	0	-	Field Hockey	Club	452	98	42
5*	20	9	4	-	Field Hockey	Varsity	1184	92	42
6	20	8	5	-	Soccer	Club	3300	74	42
7	20	1	1	126 days	Soccer	Varsity	1472	86	39
8*	21	16	12	-	Soccer	Varsity	1818	103	46
9	22	12	6	-	Soccer	Varsity	1638	119	46
10*	23	2	2	-	Rugby	Varsity	1028	107	42
11*	22	0	0	-	Rugby	Varsity	2090	ND	42
12	21	0	0	-	Rugby	Varsity	2056	88	45
AVG	21.3±1.4	4.92±5.5	3±3.5				1397.8±849.7	96.5±15.2	43.0±2.0

*Table 2.2: Demographics of athlete group. * Denotes data was obtained for gaze strategies.*

	Age (years)	SCAT 2 Score	Number of Symptoms	Time Since Concussion (days)	Sport	Level	Hours Played (Total)	Risk Taking Score	SW (cm)
1*	23	53	20	60	Soccer	Club	-	58	46
2	22	15	11	68	Rugby	Varsity	-	210	46
3	25	42	18	53	Soccer	Varsity	-	105	42
4	20	10	7	1089	Hockey	Club	-	68	40
5	23	51	17	368	Soccer	Club	-	91	42
6*	25	6	6	86	Soccer	Club	-	95	42
7*	25	56	18	368	Rugby	Varsity	-	124	52
8	24	5	4	441	Sailing	National	-	84	43
9*	20	10	9	1509	Rugby	Varsity	-	49	44
10	23	16	9	115	Rugby	Varsity	-	127	42
AVG	23±1.9	26.4±21.3	11.9±5.8	415.7±498.0				101.1±46.2	43.9±3.4

Table 2.3: Demographics of participants with PCS Denotes data was obtained for gaze strategies.*

All participants completed a health history questionnaire indicating current concussive symptoms and history of concussion, which included the SCAT2 symptom assessment (Appendix C). The SCAT2 symptom evaluation is a list of 22 symptoms of concussion ranging from emotional affect, cognitive problems, and physical pain (see Appendix C). All symptoms are self-report such that the degree to which someone possesses symptoms is subjective. Subjective reports of symptoms are recorded using a 7-point Likert scale from 0 (none) to severe (6) presence of each symptom. Scores are reported in two ways: 1) recording the number of symptoms reported; 2) calculating the sum of all symptom severities. Participants were instructed to report how they were feeling at the time of testing. Contextually, this may mean that a non-concussed individual might report feeling fatigue or low energy, as an example out of numerous other symptoms, without having suffered a concussion.

Participants also completed a risk assessment questionnaire that identified individual's tendency toward risk in financial, social, and physical situations (Appendix D; Appendix G). Participants were not included in the study if they possessed any of the following characteristics: 1) Any known neurological impairment including concussion-related symptoms that affect activities of daily living; 2) significant visual impairment (inability to see the obstacle to accurately avoid it) or cognitive impairment; 3) physical limitations limiting limb movement (inability to stand and walk comfortably for 1 hour with breaks for approximately 700m in 15m intervals); and 4) any other medical condition that would impair ability to perform daily activities. Inclusion Criteria: 1) Female; 2) Young adults and athletes: age 18-25 years; 3) visual acuity better than 20/70 (corrected vision to 20/70 or better is acceptable); 4) able to understand English instructions.

2.2 - Protocol

Participants signed the informed consent document (Appendix B). Following the provision of consent, the participant's individual shoulder width was measured. Each participant's shoulder width was recorded by measuring the widest horizontal distance across the shoulders with a tape measure to the nearest 0.5cm. This measurement was used to determine the relative aperture widths used for the individual's trials. All participants completed the perceptual judgement task (part 1, Figure 2.1) before they completed the navigational task (part 2, Figure 2.3) of the experimental trials (described below). This order of experimental conditions ensured that no participant had prior experience or familiarity with the task before being asked to perceive their action capabilities with respect to judging the pass-ability of a gap (Franchak et al., 2012).

The experiment was set up in a 14m by 6m space. A 10-metre pathway was created along the midline of the room. Two identical pole obstacles (2.45m tall x 0.17m wide) were placed at either 3m, 5m, or 7m from the start along the path on either side of the midline creating a horizontal gap (aperture) along the midline of the path (Figure 2.3). The aperture size varied between 0.9-1.7x each individual's shoulder width, at increments of 0.2, rounded to the nearest centimeter (Figure 2.3). Participants began each trial at one of four random starting locations (each location was separated by 20cm in the anterior-posterior direction) to ensure that individuals were using visual information to guide their actions, rather than relying on a consistent number of steps to guide a change in action.

2.2.1 Part 1: Perceptual Judgement Task

Two obstacles were placed 5m from the start of the path and created an aperture that varied between 0.9-1.7x the individual's shoulder width, in increments of 0.2 (Figure 2.1). Participants were asked to walk at their natural pace towards the goal, which as placed along the midline at the end of the travel path. After walking 2.5m the participants were required to provide a verbal response (while still walking) to the following question: "Do you believe you can safely pass between the obstacles without changing your body dimensions (i.e. rotating or shrugging your shoulders)?" Participants were presented with ten randomized trials (2 trials of each of the 5 aperture widths). This task took approximately five minutes to complete. All participants completed the perceptual judgement task first. This was due to an experience effect observed by Franchak, van der

Zalm, & Adolph (2010). These authors found that participants who completed the navigation task before the perceptual judgement task benefitted from action feedback.

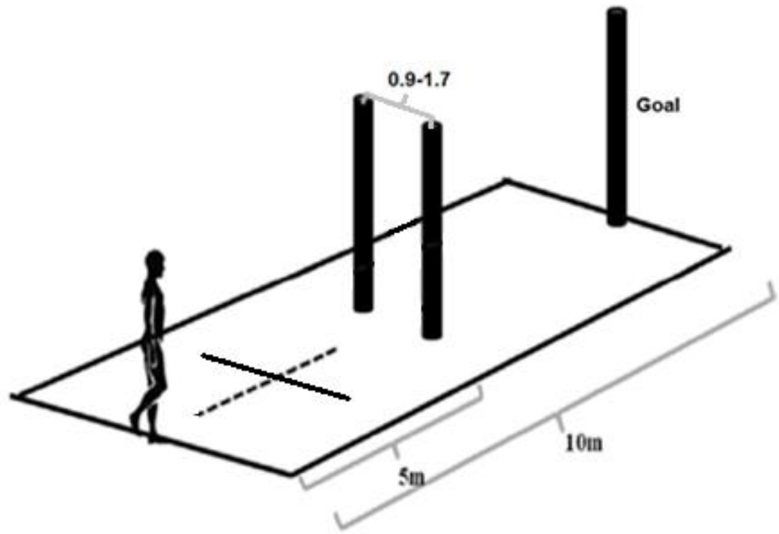

Figure 2.1: Part 1 setup. Participants were asked to walk 2.5m at their normal pace. At this point they were asked to judge whether they could safely pass through the gap (scaled to 0.9 – 1.7 x SW) without changing their body dimensions.

2.2.2 Part 2: Navigation Task

2.2.2.1. Data Recording Equipment

Participants were given a mandatory break that lasted approximately ten minutes following the perceptual judgment task. During this time, participants were instrumented with Optotrak IRED (infrared emitting diode) markers (Northern Digital Incorporated) and an Eye Tracker (ASL Mobile Eye). Infra-red light emitting diodes (IRED) markers were arranged in a rear-facing fashion, and were placed on both acromioclavicluar joints, approximately the seventh cervical vertebra, and approximately the seventh and tenth thoracic vertebrae (Figure 2.2).

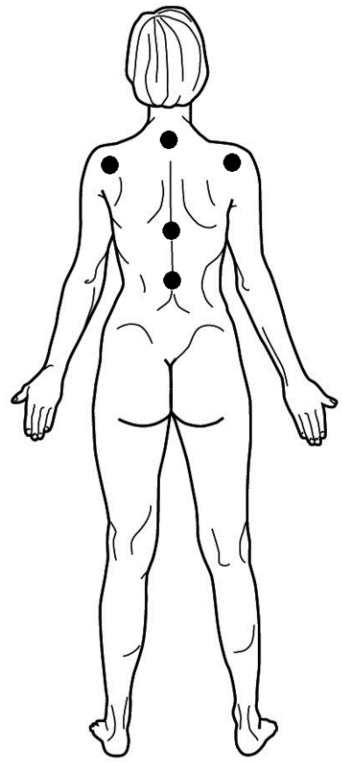

Figure 2.2: Kinematic marker setup. Markers were placed in a rear-facing orientation on the right and left acromioclavicular joints, and three markers were placed along the midline of the back at approximately C7, T7, and T12. (photo source: http://www.studyblue.com/notes/note/n/body-planes-and-sections-chapter-1-section-c/deck/6833548)

The ASL monocular Mobile Eye Tracker was then fitted and calibrated for each participant. Participants were fitted with eye-tracking glasses- equipped with two cameras and a monocle, as well as the portable recording device worn around the mid-section (at the level of the navel) with the weight carried anteriorly. Calibration was conducted using five crosshairs arranged to cover the top, bottom, left, right and central aspects of participants' field of view. The central crosshair was placed at comfortable eye-level for all participants. The calibration process required >80% accurate and clear visibility of participant's pupil, as well as accurate coordination between the camera that viewed the pupil and the visual scene. Unfortunately, accurate calibration was not achieved for all participants. Accurate gaze data was obtained for 6 (or 7 for athletes) individuals out of the total for participant groups. Regardless of whether participants were successfully setup with gaze tracking data collection, they were instructed to complete the experiment wearing the gaze tracking glasses and portable recording device in order to reduce any between-subject variability from wearing additional equipment.

2.2.2.2 Experimental Setup

The same 10m by 6m space was used to run Part 2 of the experiment. The obstacles were located at 3m, 5m, and 7m distances from the starting location on either side of the midline of the room (Figure 4). The two obstacles created one of five horizontal apertures: 0.9, 1.1, 1.3, 1.5, or 1.7 times the participants' shoulder widths. A goal was placed at the midline of the end of the 10m path.

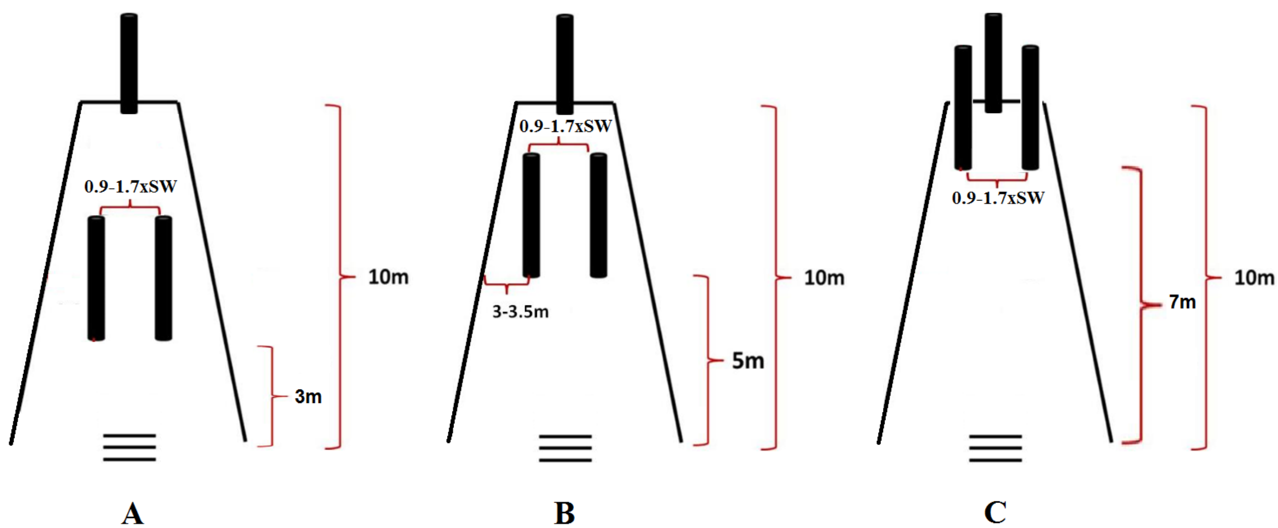

Figure 2.3: Simple illustration of experimental setup for Part 2 of the experiment. Obstacles were located A) 3m, B) 5m, or C) 7m from the starting location. The obstacles

created a horizontal gap that ranged from 0.9-1.7 times participant's shoulder widths, rounded to the nearest centimeter, at increments of 0.2.

2.2.2.3 Navigation Task

The experimenter ensured that participants understood that for each trial, they must reach the goal. Four straight, unobstructed walking trials were completed to identify participant's natural walking speed and to allow for normalized data trajectories. During the experimental trials participants were instructed to, "Walk at your normal pace along the path toward the goal and avoid colliding with the obstacles placed along the pathway". No direct instructions were given for how to avoid the obstacles, except that if they chose to pass through the gap, they were instructed not to change their body dimensions. The experimenter demonstrated and articulated the examples of rotating and shrugging shoulders to articulate that participants should walk straight through the gap. The path was clear of all other obstacles and just less than 3m of open space existed on the outer side of the two obstacles (dependent on gap width). The location of the obstacles relative to the start (i.e., 3, 5, or 7m) and the aperture widths were completely randomized. Participants completed 34 trials: 4 straight walking trials, and 2 trials of each of the aperture widths at each of the 3 obstacle distances. Numerous participants were required to repeat at least one trial. This was a result of the experimenter observing: 1) participants contacting obstacles; 2) participants rotating their shoulders to fit through the aperture; or 3) participants shrugging their shoulders to fit through the aperture. All trials that produced an error were removed from analysis. All repeated trials were added to the end of the experiment. The maximum number of trials completed was 37 (i.e., 3 extra trials, see Appendix F). This portion of the experiment took approximately twenty minutes to complete.

The entire experimental session took approximately 1 hour to complete. No participant requested breaks during the experimental trials, in addition to the mandatory break between Part 1 and Part 2. All participants completed all 10 perceptual judgement trials in Part 1, as well as a minimum of 34 trials in Part 2.

2.3 - Data Analysis

Study 1: Non-athletes were compared to athletes to identify the effect of sport-specific training on perception-action integration.

Study 2: Athletes were compared to individuals with PCS to identify concussive related deficits in perception-action integration. Individuals with PCS were compared to athletes rather than non-athletes to more carefully account for potential similarities in perceptual-motor abilities prior to their injury as related to athletic training/experience.

2.3.1 Kinematics

Any missing kinematic data was filled in through the use of a cubic spline interpolation. A weighted average calculation was used to estimate the location of Centre of Mass (COM) in the Anterior-Posterior (AP) and Medial-Lateral (ML) directions through the use of the trunk IRED markers. These COM estimates allowed for the calculation of the average COM and changes to individuals' walking speed, onset of travel path deviations, ML COM position at the time of passing the obstacles, and variability in ML COM during the approach. A deviation was said to have occurred if the ML COM position during the approach phase towards the obstacles was ±2 standard deviations from the mean of straight walking trials. AP safety margin was identified as the position between the participant's COM and the obstacles at the point at which participants initiated a deviation in the anterior-posterior direction. ML safety margin was defined as the horizontal position between the participant's closest shoulder and the outside edge of the obstacle at the time of passing during the avoidance trials.

COM metrics were divided into the approach and time-of-passing phases of the experimental task. The approach phase was defined as the distance leading up to the obstacles, but did not include interactions with the obstacles. The time-of-passing phase was defined as the point at which participants crossed the obstacles, choosing to navigate through or around the gap they created. This time point was identified through assessing participants' action strategies 1m anterior to the location of the obstacles.

The time-of-passing phase was a very specific time point, at which the participants were physically passing the obstacles. This data was identified by extrapolating the obstacles' distance from the origin in the AP direction, and identifying the participants' kinematics at this particular instant. The absolute value of the ML COM position at the time of passing the obstacles was averaged across two trials to assess travel path differences between groups. ML COM variability at the time of passing the obstacles was also assessed. Standard deviation was obtained, identifying the consistency in travel path choice between the two trial repeats of each condition.

IBM SPSS Statistics software was used to run statistical analyses. Mixed-model ANOVAs (between factor: groups (2); within factor: gap size (5) and obstacle distance (3)) were conducted comparing: ML COM at time of passing the obstacles; AP and ML safety margins; and average speed during the approach as well as speed at the time of passing the obstacles. Statistical power was reported (instead of effect size) as this value includes an aspect of statistical effect size as well as sample size. As the current study employed analyses with group N=12, it was important to note the influence of sample on the effect. Due to the fact that statistical power (and effect size) was small-to-medium at the $p<.05$ level, significance has been reported at a maximum of the $p<.01$ level to identify only those effects with strong statistical power. Bonferroni post-hoc analyses were employed in the case of significant main effects.

2.3.2 Perceptual Judgements

Participants "Yes" or "No" responses were binary coded (Yes = 1; No = 0). A tally score was calculated for the two trials of each gap width to identify consistency in decision making. The narrowest gap width that resulted in two "Yes" responses was identified as being the participant's Critical Point. This value was entered into an independent samples T-Test to compare between groups.

2.3.3 Gaze Tracking

A smaller sample size from each group was used to analyze gaze tracking data (N=6 non-athletes, N=7 athletes, N=4 PCS). This was due to the nature of gaze tracking equipment. Accuracy of gaze tracking calibration was highly dependent on lighting conditions, eye-shape (i.e. oval versus round; hooded eyelids), and fit of the equipment As such, gaze tracking was attempted on all participants, but accurate, usable data was only obtained on a total of 17 individuals. All gaze tracking data were obtained for the approach and time of passing phases of each trial.

Fixations were defined as focussed gaze on a single object or location within 3 degrees of visual field for a minimum of 100ms (Carpenter, 1988). This is the minimum amount of time required to recognize a stimulus (Vickers, 2007). A frequency count was taken identifying the number of objects fixated during the approach phase of each trial. Chi-square analyses were employed comparing the number of fixations between groups, conditions, and action strategies.

Durations of fixations during the approach phase were measured to the nearest millisecond. A mixed-model ANOVA was conducted comparing average fixation duration between groups, gap widths, and obstacle distances (2 x 5 x 3). Final fixation was defined as the last fixation before participants passed the obstacles. Duration of final fixation was also measured to the nearest millisecond. This metric was assessed in a mixed-model ANOVA comparing groups, gap sizes, and obstacle distances (2 x 5 x 3). Correlations were also employed to assess whether number or durations of fixations were related to amount of athletic training (in hours). Both Pearson and Spearman correlations were employed as parametric and non-parametric outcome measures were assessed (i.e. duration of fixation versus number of fixations).

Further analyses were conducted to compare gaze strategies between action strategies. Chi square tests were employed to compare number of fixations between trials when participants chose to deviate around or pass through the gap created by the obstacles. Fisher's Exact Tests were employed as frequency counts in certain cells of the data matrix were equal to or less than five. A t-test was employed to compare the duration of fixations between action strategies (deviate versus through). A Pearson correlation was conducted to identify a relationship between travel path choice (ML COM position at the time of passing the obstacles) and average fixation duration.

3. Results: Study 1

3.1 Travel Path

It was hypothesized that athletes would demonstrate more efficient navigation to the goal by maintaining their straight trajectory for a greater number of trials (Fajen & Warren, 2003); whereby athletes would choose to fit through gaps that were a smaller proportion of body-size compared to non-athletes. To assess this, ML COM position at the time of passing the obstacles (TOP) was determined. This value was calculated by identifying the distance of each individual's COM from the midline of the room at TOP. Small values (those close to 0) indicated participants chose to walk between the obstacles, up the midline of the travel path, where large values (>30cm) indicated a change in travel path (for direction of deviation see Appendix E).

A main effect of gap size was identified ($F_{(2.58,\ 88)}$=42.59, $p<.01$, $\beta>.99$). Post hoc analysis revealed that participants tended to deviate around obstacles that created gaps of 0.9 and 1.1 x SW ($\bar{x}$=55.11, 35.33cm respectively) and walked through gaps greater or equal to 1.3x SW ($\bar{x}$= 7.98, 4.33, 5.72cm respectively; $p<.01$). No effects of group or obstacle distance were identified through this analysis (Figure 3.1 & 3.2).

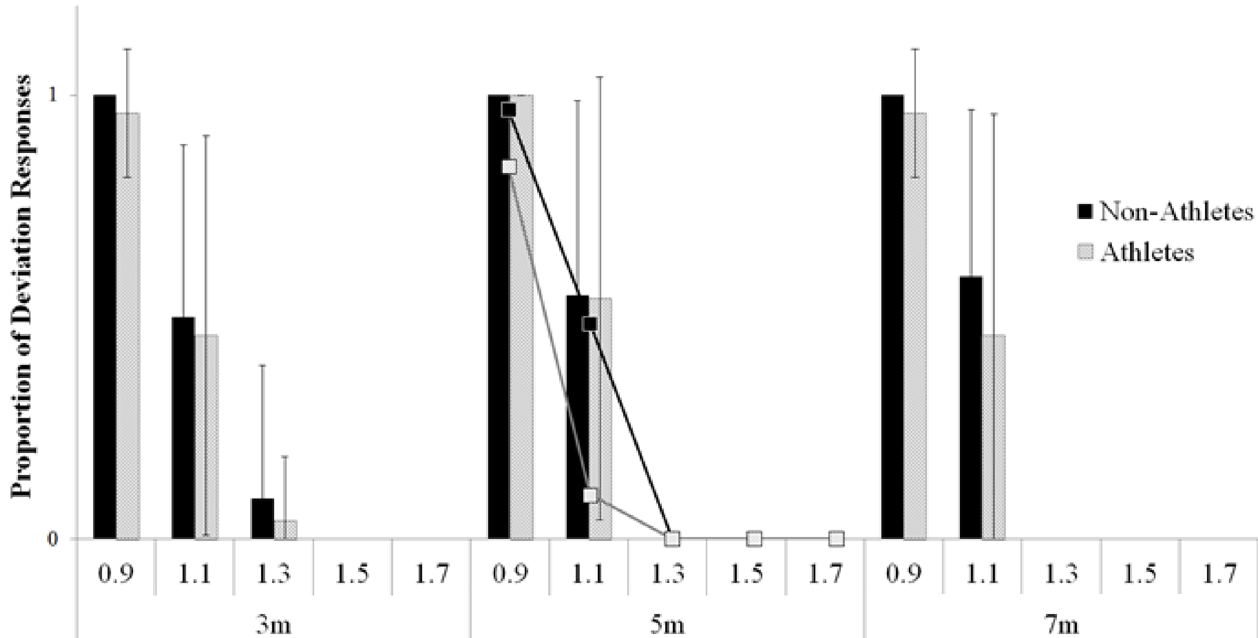

Figure 3.1: Proportion of trials where participants navigated around the obstacles. Proportion of responses where participants did not perceive they could safely navigate through the graph is overlaid.

<u>*3.1.1 Travel Path Variability*</u>

As no group differences were identified in decision making, perhaps one group was more variable in their choice of travel path than the other. If athletes were more consistent in their decision making, it could be concluded that they were more precise at perceiving for action. Analysis of standard deviation across trials of ML COM position at TOP revealed a main effect of gap size ($F_{(2.94, 68)}$=4.65, p<.01, β =.67), where both groups were identified to have more variable ML COM position when passing obstacles that created gaps of 0.9 and 1.1x SW ($\bar{x}$=23.05, 34.99) than gaps of 1.5 and 1.7 x SW ($\bar{x}$=5.34, 9.72). No other effects or interactions were identified (Figure 3.2).

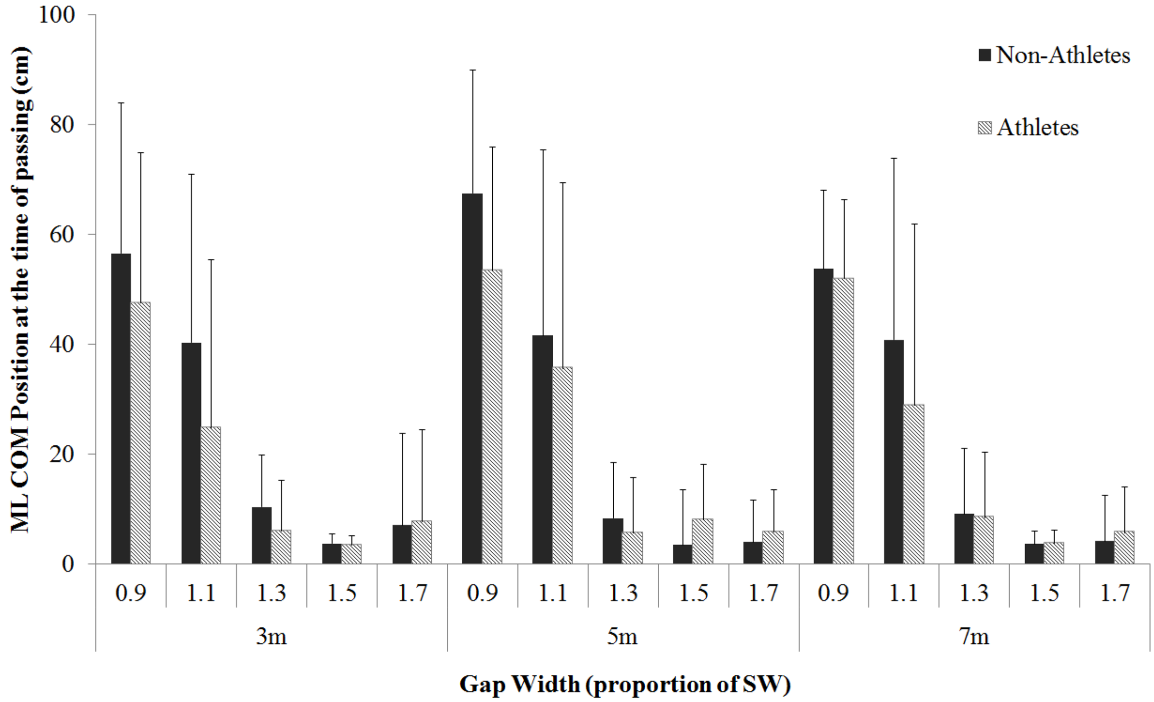

Figure 3.2 – Navigational strategies are displayed as a deviation from the midline of the travel path at the time of passing the obstacles (TOP). Large values indicate a change in action strategy (avoidance) where small values indicate participants chose to navigate through the gap. A main effect of gap width was reported where MLCOM position was significantly greater when participants passed obstacles that created gaps of 0.9 and 1.1 x SW, indicating that both groups tended to pass through gaps that were 1.3 x SW or greater. No effect of distance was identified.

3.2 Perceptual Judgements

As navigational strategies did not differ between groups, perceptual judgement strategies were assessed to identify whether participants were similarly judging their body size for navigation, regardless of whether they had sport specific training. If groups were to differ on this measure, with athletes perceiving safe passage through gaps closer to their body size, it could be concluded that athletes better perceive their shoulder width for more accurate navigation. Thus, this information would assist in our understanding of athletes' sport-specific navigational strategies. Participants were asked to judge whether they believed they could safely pass between a gap (0.9-1.7 x SW) placed 5m from the start. "Yes" or "No" responses were recorded without participants having to physically passed through the gap. Group differences were assessed by identifying the smallest gap width that participants always identified as safely passable across the two repeated trials (two "yes" responses). A t-test was conducted comparing the smallest gap width participants deemed safely passable. Results revealed no differences between athletes ($\bar{x}$=1.1± .12) and non-athletes ($\bar{x}$=1.19± .11) on this measure ($t_{(21)}$= 1.93, p=.07), where both groups perceived gaps 1.1 x SW or larger to be safely passable (Figure 3.1).

Therefore, athletes and non-athletes perform similar navigational strategies, and perceive safe navigation similarly. However, as these results were not conducive with the original hypotheses, further analyses were conducted to assess dynamic stability between groups. Dynamic stability was also assessed to identify group differences in behavioural dynamics.

3.3 Dynamic Stability

ML COM variability during the approach phase is an excellent indicator of dynamic stability and is correlated with aperture crossing behaviours (see Hackney & Cinelli, 2013). Results indicated that there were no significant effects or interactions between obstacle distance and/or groups. A non-significant effect was identified for gap width ($F_{(1.99, 56)}$=3.96, p=.03, β =.39), where slightly greater variability was observed when participants were approaching obstacles that created gaps equal to 0.9 x SW ($\bar{x}$=4.47cm) compared to other gap sizes.

3.4 Related Behaviours

3.4.1 Speed

Gait speed during the approach (cm/s) was assessed. It was hypothesized that when approaching obstacle conditions that created a greater perceptual challenge (i.e. decision making when approaching gaps of 1.1 x SW), participants would reduce their walking speed. No significant effects or interactions were identified between groups or conditions on gait speed.

Likewise, gait speed at the time of passing the obstacles (cm/s) was assessed. It was hypothesized that when passing obstacles that created a greater perceptual challenge (i.e. navigating through gaps of 1.3 x SW), participants would reduce their walking speed. No significant effects or interactions were identified between groups, gap sizes, or obstacle distances (Figure 3.3).

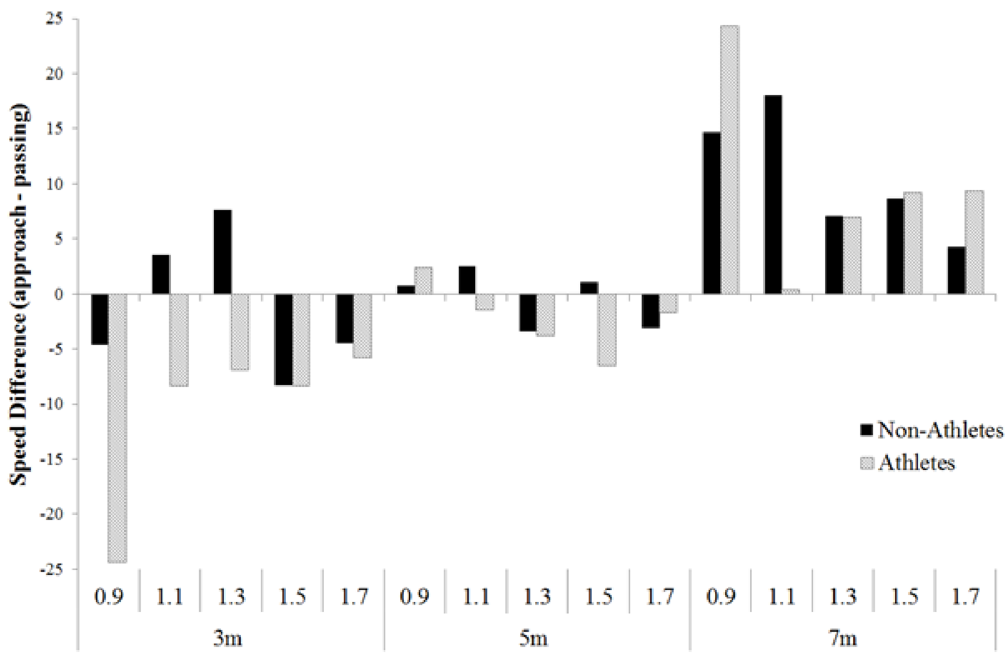

Figure 3.3: Speed changes for each condition. Speed at the time of passing the obstacles was subtracted from the speed during the approach phase. Positive values indicate participants walked faster when they were approaching the obstacles, and slowed down when crossing the gap. All speeds are reported in cm/s.

3.4.2 Safety Margin

The AP safety margin was calculated for trials when participants chose to deviate around the obstacles, instead of passing through the gap. AP safety margin was determined by identifying AP COM position when each participant deviated from a straight path (AP point at which ML COM fell outside of ±2 SD from the straight through travel path). AP safety margin is a measure to quantify the level of threat or repulsion of obstacles (i.e., larger value indicated a greater threat).

Results revealed a main effect of obstacle distance ($F_{(1.43, 18)}$=24.27, p<.01, β =.99). Post hoc analyses identified AP safety margin was significantly greater when the obstacles were located 7m from the start ($\bar{x}$=238.5cm), compared to obstacles at 5m and 3m ($\bar{x}$=174.6cm and 119.3cm respectively, p<.01). Similarly, AP safety margin was significantly larger when approaching obstacles located at 5m compared to those at 3m (p<.01) (Figure 3.4).

A trend, with small-to-medium statistical power, was identified for an interaction between obstacle distance and gap size ($F_{(1.77, 18)}$=5.35, p=.019, β =.45). Participants maintained a larger AP safety margin when approaching obstacles that created gaps of 0.9 x SW, located 7m from the start, compared to gaps of 1.1 x SW ($\bar{x}$=247.83cm and 229.15cm respectively). In contrast, participants maintained a larger AP safety margin when approaching gaps of 1.1 x SW, located 5m from the start, compared to gaps of 0.9 x SW ($\bar{x}$=184.59cm and 164.62cm respectively). However, no differences were identified between the AP safety margin when participants approached gaps of 0.9 and 1.1 x SW located 3m from the start ($\bar{x}$=122.09cm and 116.42cm respectively).

A trend of an interaction between obstacle distance, gap size, and group was identified ($F_{(1.77, 18)}$=5.36, p=.019, β =.45). Further examination revealed that participants interacted with obstacles located 3m from the start differently, compared to the other two obstacle distances. Athletes tended to maintain a larger AP safety margin when approaching gaps of 0.9 x SW at 3m ($\bar{x}_{0.9}$=123.28cm versus $\bar{x}_{1.1}$=94.64), compared to non-athletes who tended to maintain a greater AP safety margin when approaching gaps of 1.1 x SW at 3m ($\bar{x}_{0.9}$=120.90cm versus $\bar{x}_{1.1}$=138.20cm).

ML safety margin was also calculated, which is the distance between the outer edge of the obstacle and the most lateral aspect of the participant's closer shoulder. Again, this was only calculated for the trials in which participants chose to deviate around, rather than walk through the gap created by the obstacles. ML safety margin is a measure of the amount of space that individuals require between themselves and an obstacle at the time of passing. No main effects or interactions were identified through this analysis (Figure 3.3).

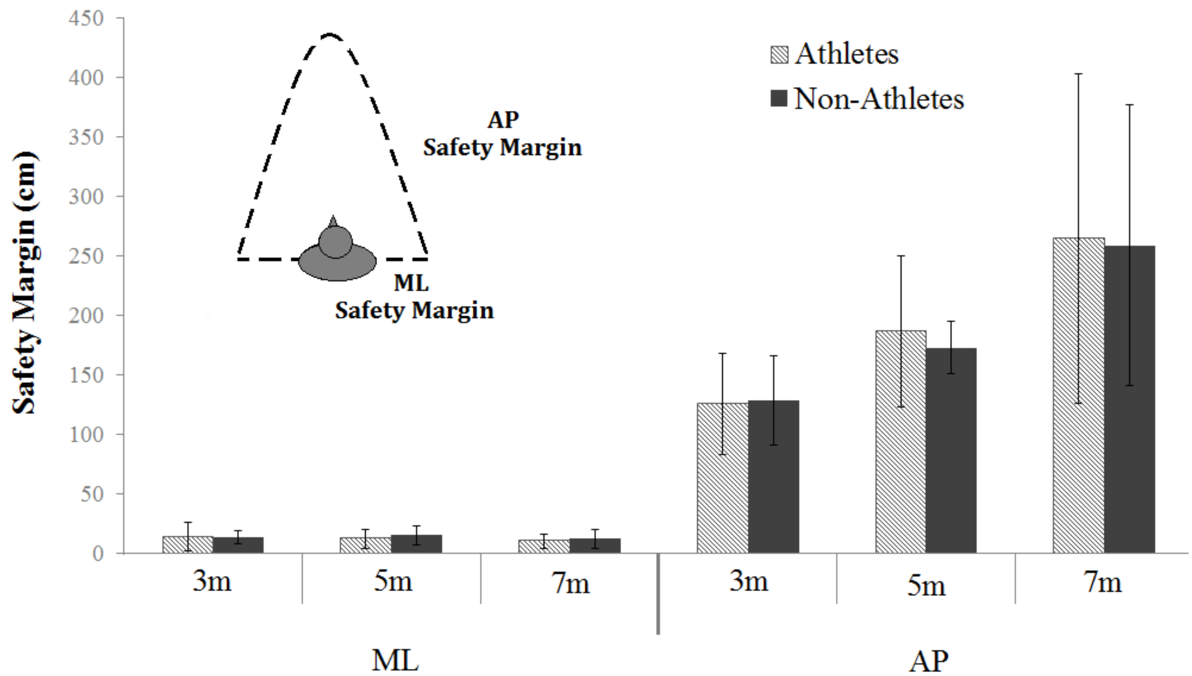

Figure 3.4: Condition and group differences in safety margin (cm). Anterior-posterior (AP) safety margin was found to increase with increasing obstacle distance, but was not found to differ between groups. These results indicate that participants chose to deviate around obstacles with a greater margin of safety in the AP direction with increasing obstacle distance. Medial-Lateral (ML) safety margin was not found to differ between groups.

<u>3.5 Visual Sampling Strategies</u>

3.5.1 Quiet Eye

Numerous studies by Vickers and Williams (collaborative and not) have identified gaze strategies of fewer, longer fixations that correlate with more successful action strategies in elite and expert athletes. These athletes have been found to make fewer fixations of longer duration when completing both discrete and continuous motor tasks of their respective sports (see Vickers 2007 for a review). For the purposes of this study, the duration and number of fixations were identified during the approach phase (up to the time of passing) of each trial. It was hypothesized that athletes would employ fewer, longer fixations than non-athletes. Furthermore, the work of Vickers has identified the presence of a 'Quiet Eye', which she has deemed as a long duration final (task relevant) fixation before the motor task is carried out. It was hypothesized that athletes would demonstrate the Quiet Eye, in that, they would demonstrate a longer final fixation before passing the obstacles than non-athletes.

A main effect of group was identified between length of final fixation (in seconds) ($F_{(1,7)}=8.35$, $p<.05$, $\beta=.70$) where athletes ($\bar{x}=2.60$s) demonstrated significantly longer final fixations than non-athletes ($\bar{x}=.48$s). No main effects or interactions were observed for obstacle distance or gap width. No main effects or interactions were observed within athletes or non-athletes.

3.5.2 Number of Fixations

Non-athletes were found to make significantly more fixations (m=7.61) than athletes (m=5.88) ($X^2_{(17)} = 34.49$, $p<.001$). The number of fixations also differed significantly among obstacle distances ($X^2_{(58)} = 66.98$, $p<.05$) with the average number of fixations increasing with increasing obstacle distance (m_{3m}=5.52, m_{5m}=6.60, m_{7m}=7.64). Group differences were examined at each obstacle distance. Non-athletes were found to make significantly more fixations than athletes when obstacles were located 7m from the start ($X^2_{(17)} = 46.42$, $p<.01$). No differences were identified between groups when obstacles were located 3m or 5m from the start. Finally, the number of fixations did not differ significantly among gap widths (Figure 3.5).

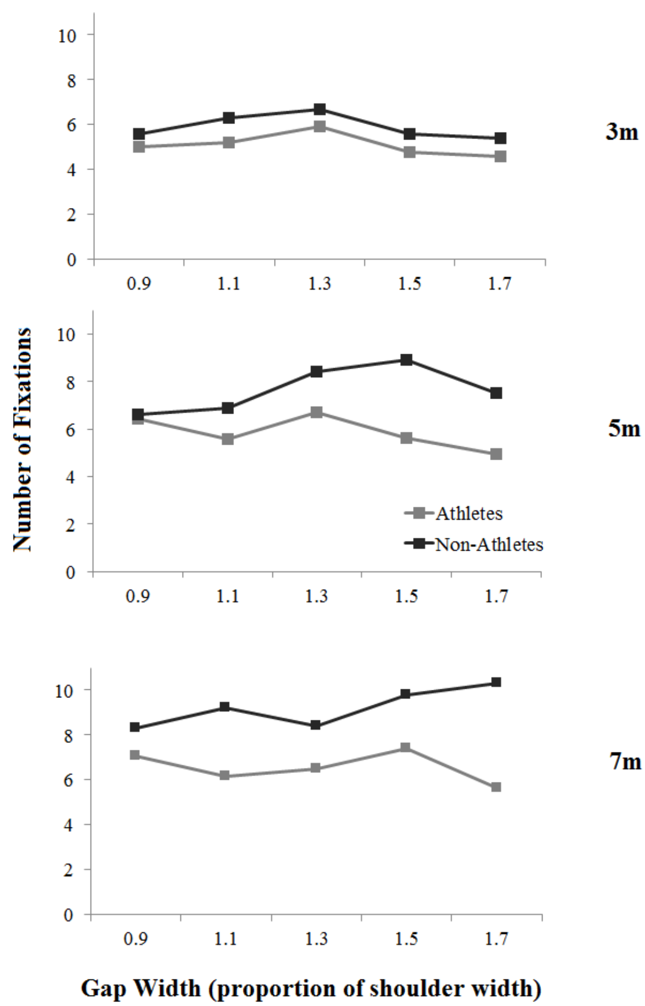

Figure 3.5: Average number of fixations for each condition. Athletes were found to make fewer fixations than non-athletes, regardless of condition (p<.001). Number of fixations

was also found to increase with increasing obstacle distance ($p<.05$), resulting in an interaction between group and obstacle distance, where athletes made significantly fewer fixations than non-athletes when obstacles were 7m from the start ($p<.01$).

3.5.3 Average Fixation Duration

A main effect of group was identified between average fixation duration (in seconds) during the approach phase ($F_{(1,8)} = 5.3$, $p<.05$, $\beta = .53$) with athletes demonstrating significantly longer fixations than non-athletes ($\bar{x}=1.33\pm1.44$ seconds compared to $\bar{x}=.32\pm.15$ seconds). A main effect of group was identified for obstacle distances of 5m and 7m ($F_{(10,1)} = 5.97$, $p<.05$, $\beta = .60$; $F_{(9,1)} = 5.47$, $p<.05$, $\beta = .55$). However, the effect of group was not significant when obstacles were located 3m from the start ($F_{(9,1)} = 5.04$, $p=.051$, $\beta = .52$), although this effect is nearing significance (Figure 3.6).

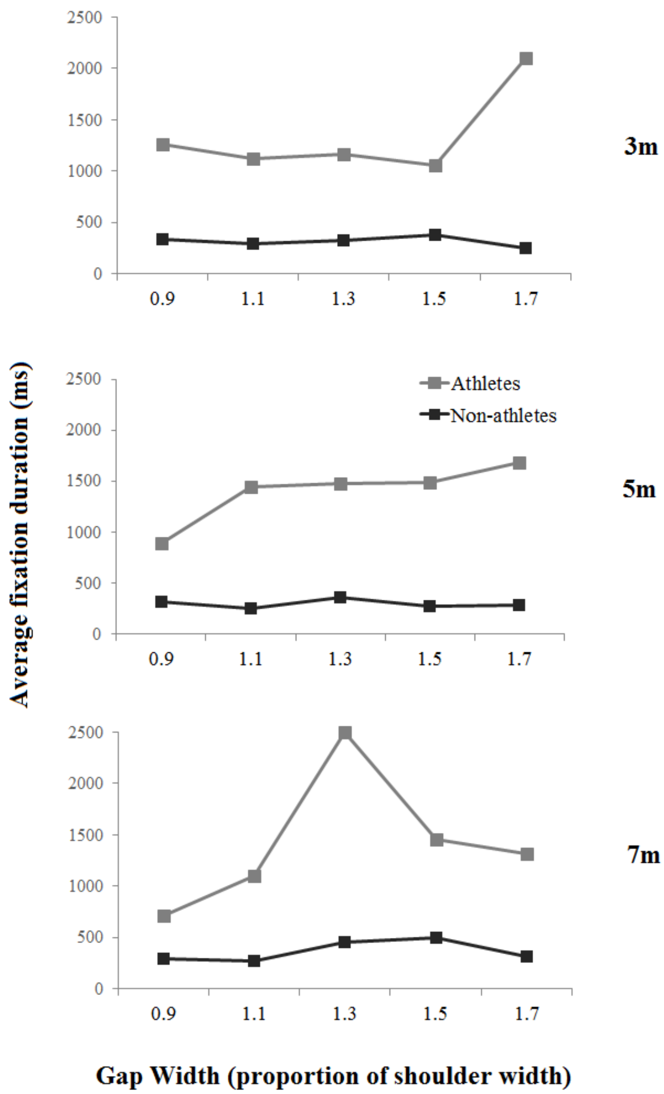

Figure 3.6: Average fixation duration for each condition. Athletes were found to make longer fixations than non-athletes, regardless of condition (p<.05). Further analysis revealed that this relationship held true when obstacles were located 5m and 7m from the start, but not at 3m.

Athletes demonstrated more variable fixation durations than non-athletes. As a group, athletes were found to have significantly more variable gaze fixation durations than non-athletes ($F_{(1,8)} = 8.54$, $p<.05$, $\beta = .73$). No effect of obstacle distance was identified, nor were any effects of gap size identified. A similar analysis was conducted for coefficient of variation, to standardize variability across participants. Similarly, athletes were found to have significantly more variable gaze fixation durations than non-athletes ($F_{(1,8)} = 17.15$, $p<.01$, $\beta = .95$).

In order to better understand this finding, analyses were conducted to understand intra-group differences in gaze fixation strategies. Athletes may have also demonstrated different gaze strategies as a function of their level of expertise. Thus, further analyses of fixation strategy were employed to determine if gaze metrics could better define action strategies. Correlational analyses were conducted to compare hours of training with average length of fixation and average number of fixations across athlete participants. Athletes reported the approximate total number of hours they had trained in their particular sport ($\bar{x}=765.8 \pm 545.7$). Amount of training did not correlate with average length of fixation ($r_{(7)}= -.11$), nor was it found to correlate with number of fixations ($r_{(7)}= -.18$). Amount of training also did not significantly correlate with consistency in action strategy as determined using the ML COM variability at the time of passing, ($r_{(7)}= .57$, $p=.09$) and decision making consistency as a percent change in travel path ($r_{(7)}=.37$, $p=.15$).

3.5.4 Gaze Behaviours Specific to Travel Path Choice

Decision making (deviate around or pass through the gap) may be related to the gaze strategy employed for particular trials. If participants demonstrated different types of gaze strategies across decision-making (regardless of experimental group), we can better understand the relationship between perception and action.

The number of fixations was compared between trials when participants chose to deviate around to those in which they chose to walk through the gap created by the obstacles (i.e. action strategy). No difference was observed between number of fixations made during the approach phase of the task for trials in which the participants chose to deviate around to those that they passed through (p=.43) (Figure 3.7a).

It was thought that if an individual demonstrated differential decision making then she would produce more fixations prior to passing the obstacles. However, consistency in travel path choice (standard deviation of ML COM position at the time of passing the obstacles) did not correlate with fixation duration ($r_{(179)}$ =.02, p=.46). Similarly, fixation durations are thought to reflect the amount of time required to process visual information (Cinelli et al., 2009). A t-test was conducted to determine differences in fixation duration for trials when participants chose to deviate around or walk through the gap created by the two obstacles. Fixation durations were found to be significantly longer for trials where participants chose to walk through the gap ($\bar{x}$=1.06±1.64) than when they chose to deviate around ($\bar{x}$=.69±.71; $t_{(311.87)}$=- 2.79, p<.01) (Figure 3.7b).

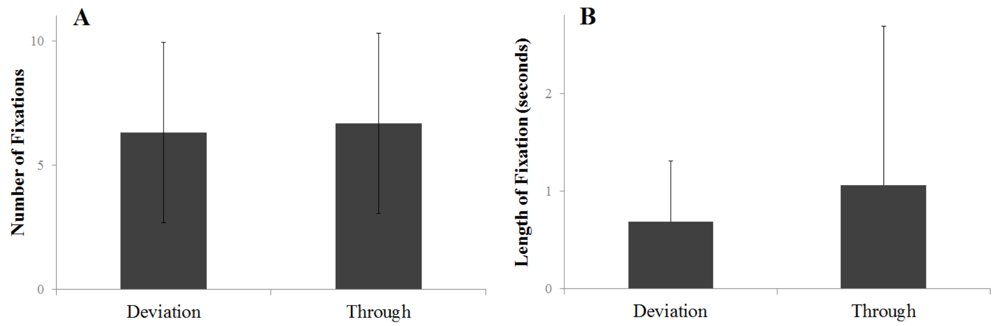

Figure 3.6: A) Average number of fixations per action strategy. No differences were identified between action strategies when comparing number of fixations B) Average length of fixation per action strategy. Participants were found to make significantly longer fixations when passing through gaps than deviating around.

4. Discussion: Study 1

The purpose of this study was to determine if athletes demonstrate sport-specific navigation strategies when avoiding two obstacles, which create a gap, in open space. We defined sport-specific navigational strategies as the ability of athletes to perform action strategies with a more accurate perception of body size, allowing them to pass through gaps that were a smaller proportion of their shoulder widths, compared to non-athletes. It was hypothesized that under increased temporal constraints (objects located closer to start), athletes would further demonstrate these more accurate action strategies. This, however, was not the case. No differences were observed between action strategies of athletes and non-athletes at any obstacle distance. Furthermore, no dynamic stability differences were identified between these two groups. Yet, athletes demonstrated fewer, longer visual fixations than non-athletes. These results suggest that athletes have more effective visual sampling strategies, such that, they obtain salient visual information from fewer environmental features to perform the task compared to their non-specifically trained counterparts.

Affordance theory dictates that perception and action are cyclically related. However, task constraints play a vital role in how and what action strategies individuals perform (Warren, 2006). In order to successfully complete a task, one must consider the environment, their own action capabilities, but also the constraints of the task (i.e. experimental instructions). Through behavioural dynamics, we gain a more holistic understanding of the necessity of goal-directed outcomes to how individuals integrate perception and action. Recall that behavioural dynamics can be defined as the inclusion of task constraints in addition to our understanding of affordance theory (Fajen & Warren, 2003; Warren, 2006; Fajen, Riley, & Turvey, 2008). Given our experimental instructions to locomote to the goal without colliding with the obstacles, we can consider the goal an attractor and the obstacles repellers. It was hypothesized that as the gap size created by the two obstacles decreased (i.e., obstacles closer together), participants would choose to navigate around the gap because the repulsion vectors from each obstacle would overlap at the aperture, making a passage through the obstacles not desirable. In such situations, the effects of the repulsion vectors from the obstacles in the AP direction would increase as the participants approached them to the point in which the participants would deviate from their straight path resulting in a consistent AP safety margin between themselves and the obstacles (Fajen and Warren, 2003). Since the magnitude of the repulsion vectors surrounding the obstacles are believed to be consistent, it was believed that a consistent ML safe margin would be maintained between the participants and the closest obstacle at the time of passing (TOP) (Fajen and Warren, 2003). It was hypothesized that athletes, who are specifically trained to safely navigate through small gaps in open space, would navigate through narrower gaps than non-athletes, but this was not found to be the case. Therefore, it is possible that the magnitude of repulsion from the obstacles is not dependent on individuals' athletic or training attributes but rather those pertaining to the obstacles themselves (environmental attributes).

4.1 Travel Path

Both athletes and non-athletes tended to deviate around obstacles that created gaps of 1.1 x SW or smaller, and walk through gaps created by obstacles that were equal to or greater than 1.3 x SW (Figure 3.1). These findings are consistent with previous work that identified the aperture width to shoulder ratio (A/S) that elicited a change in action strategy was equal to approximately 1.3 times one's widest body dimension (Hackney et al., 2013; Warren and Whang, 1987; Franchak, Celano, & Adolph, 2012). However, Higuchi et al. (2011) noted that the action capabilities of athletes were only apparent when participants were required to run through a gap. Indeed, it appears that athletic prowess in navigation may only be related to action capabilities, when gait speed is increased (Gerin-Lajoie et al., 2007). Therefore, both participant groups in the current study were using body-scaled information, more so than their action capabilities, when determining whether to deviate around or walk through the gaps. This is contrary to what Fajen (2013) believes guides actions in dynamically changing environments. However, for static environments, it is possible that passage through gaps created by static obstacles is not desirable when the gap is smaller than 1.4 times one's shoulder width because that is the point at which the repulsion vectors from the obstacles overlap. Gerin-Lajoie and colleagues (2007) found that athletes performed a navigation task faster, and more efficiently (fewer path deviations when way-finding) compared to non-athletes. These results suggest that athletes do perform navigational tasks with more efficiency than non-athletes. Yet, it must be noted that the task employed by Gerin-Lajoie et al. (2007) was a more complex environment, and participants were required to navigate at a faster pace, potentially allowing for use of action capabilities in addition to body-scaled information.

4.1.1 Travel Path Variability

When examining ML COM variability at the time of passing, no effect of obstacle distance was identified, nor were group differences (Figure 3.2). Both athletes and non-athletes demonstrated more variable action strategies when interacting with obstacles that created gaps of 0.9 and 1.1 x SW (Figure 3.2) regardless of obstacle distance. Previous research has found that young adults are highly consistent in their use of vision to guide action strategies when interacting with gaps at or near their shoulder width (Warren & Whang, 1987; Hackney & Cinelli, 2013; Higuchi et al., 2011). Hackney & Cinelli (2013) revealed that younger adults (same age range as both of the current groups) demonstrated highly consistent action strategies, regardless of the gap size created by the obstacles. Yet, there is a unique difference between our paradigm and those previously reported: the inclusion of varying obstacle distances. Hackney & Cinelli positioned all obstacles 5m from the starting location, at gap widths varying 0.6- 1.8 x SW (2013). As the current paradigm includes obstacles at 3 varying locations, and such locations were randomized, the current results likely illuminate increased inherent variability in how participants performed the task. Perhaps this factor increased the relative amount of on-line control required to complete the current experiment, compared to those previously reported (Hackney & Cinelli, 2013). Therefore, if participants were adopting a relatively new strategy for each trial, as opposed to adopting an entirely *a priori* strategy as previously suggested (Hackney & Cinelli, 2013; Higuchi, 2013), then this may account for the increased variability observed in the current study.

4.2 Perceptual Judgements

A key outcome measure to assist in our understanding of perception-action integration capabilities was to assess participants' perceptual judgements. Participants' perceptions of safe navigation were assessed prior to examining their physical interactions with the obstacles. This task required participants to walk a short distance toward the obstacles and provide a verbal response as to whether they could safely pass through the gap without changing their body dimensions. In fitting with affordance theory, it was important to assess perceptual judgements while individuals were moving, as this theory dictates that one must move in order to perceive for action (Gibson, 1979). Both athletes and non-athletes perceived that they could safely navigate between two obstacles that created gaps of 1.1 x SW or greater without rotating their shoulders (Figure 3.2). Participants' perceptions of safely navigable gaps are similar to findings by Warren and Whang (1987). These authors concluded that regardless of whether their participants were stationary or moving, all individuals perceived they could pass through gaps equal to 1.16-1.18 x SW without changing their body dimensions. The differences in the study by Warren and Whang (1987) resulted from gap widths being measured in extrinsic units, in centimeter increments, where the current study only included gap sizes that were a direct proportion of body size. The similarity between the current study's results and those of Warren and Whang (1987) demonstrate consistent perceptual judgment strategies across groups of younger adults. Participants from both studies demonstrated the use of body-scaled information to create accurate perceptual judgements of safe navigation. This aligns with a key feature of affordance theory- that individuals use their own physical constraints to accurately perceive environmental cues for action. These results also suggest that specifically trained athletes do not demonstrate superior perceptual judgements on this task, and instead, produce perceptual judgments similar to that of untrained individuals. Perhaps this null finding is a result of task constraints. As participants were required to walk and athletes are specifically trained on making perceptual judgements while running in the sporting setting, their training may only result in different perceptions of actions when the form of locomotion was similar to that in which they were trained (i.e., running) (Higuchi et al., 2011). However, another potential contributing factor to the null finding between groups may result from high response accuracy of younger adults (Hackney & Cinelli, 2013). Perhaps the simplicity the task was the cause of both groups performing similarly as they performed similar perception-action integration strategies on this experimental task.

It has been well documented that one must move to accurately use vision for adaptive locomotion (Cinelli, Patla, & Allard, 2009; Hollands, Patla, & Vickers, 2002; Patla, 1998). Yet, this does not explain why stationary gap crossing tasks result in similar perceptual abilities regardless of whether participants are stationary or moving (Warren & Whang, 1987; Fajen, Diaz & Cramer, 2011; Hackney & Cinelli, 2013). Perhaps these findings enlighten a unique attribute of the populations at hand such that younger adults:

1) are highly accurate in perceiving their body size for action (Warren, 1984; Franchak et al., 2010; Hackney & Cinelli, 2013); and/or 2) dynamic stability is under great control such that the visual information differences that occur as a result of moving do not significantly influence perception from when one is stationary. Therefore, perhaps younger adults, regardless of training, are highly efficient at this task and performing at a ceiling level. If so, this task may not be complex enough to disentangle group differences between athletes and non-athletes, unless dynamic stability differences exist between groups (see below). It has been previously found that action strategies do not differ between specifically trained athletes and non-athletes when completing a gap crossing task while walking in confined space and running in unconfined space (Higuchi et al., 2011; Hackney et al., 2014) but Fajen and colleagues (2009) have suggested that athletic prowess in perception-for-action is well documented throughout the literature. These incongruent findings may therefore confirm that in order to assess athletic perceptual proficiency, one must identify more context-specific aspects of sport to more accurately assess athletic-related expertise in perceptual judgments pertaining to action capabilities (i.e. while running and/ or with moving obstacles)

4.3 Travel Path & Perceptual Judgement Discrepancies

Decision making to determine safely passable gaps was similar between the navigation and perceptual judgement tasks, in that, participants determined that gaps just larger than body size were safely passable. However, the Critical Points (i.e., the onset of a change in action or perception) were not identical between the two tasks; participants perceived they could pass through smaller gap widths than they did when physically interacted with the obstacles (1.1 x SW versus 1.3 x SW, Figure 1). This discrepancy between perceived and navigated passable and impassable gaps was also found by Warren and Whang (1987). These authors suggest that the discrepancy between their navigation and perceptual judgement tasks was due to the semantics of their instructions, in that, the authors believed they inadvertently told participants to be less cautious in the perceptual judgement task. Within the tenets of behavioural dynamics, such semantics would likely result in different outcomes, as observed; if participants differentially interpreted instructions of “safe passage” or “obstacle avoidance” it may result in their performing different navigational strategies. The current study may have semantically erred in the opposite direction as Warren and Whang (1987). Participants were asked if they could *safely* navigate through the gap, without changing their body dimensions, during perceptual judgement trials. In experimental trials, participants were not given specific instructions on how to navigate, but were simply told not to collide with the obstacles or change their body dimensions. Regardless of the semantics of task instruction, these two studies suggest that younger adults, irrespective of athletic training, tend to act more cautiously when physically interacting with the obstacles, than when simply performing perceptual judgements.

Perhaps the differences in perception and action emerged from experimental constraints. Participants were instructed to either deviate or walk straight through the gap. This constrained their action strategies to one of two responses. Warren and Whang (1987) had participants perform confined gap crossing, which constrains participants to walk straight through the gap or rotate their shoulders while doing so. Similarly, the perceptual judgement task was a question with a yes/ no response. It is possible that these dual-response systems are not naturally occurring task-constraints for perception-action integration capabilities during gap navigation in the environment; perhaps it is more natural to have a greater number of potential action strategies. With fewer task constraints, results may have been more cohesive between perceptual judgement and navigation trials. Regardless of causation, it can be concluded that both athletes and non-athletes have similar perception-action integration strategies, and that these findings support those previously identified (Warren & Whang, 1987; Hackney & Cinelli, 2013). Both groups demonstrated similar decision making strategies, suggesting that the behavioural dynamics of the task did not differ between those with and without athletic training. Yet, to more confidently conclude this, further analysis must be conducted to assess behavioural dynamics in terms of participants' action capabilities.

4.4 Dynamic Stability

As understood from behavioural dynamics and affordance theory, individuals' action capabilities are integral to understanding their action strategies. Franchak and colleagues (2012) concluded that obstacle interactions and safety margin were related to gait kinematics. Medial-lateral body sway during locomotion has been found to play a vital role in how individuals create action strategies when navigating gaps (Franchak et al., 2012; Hackney & Cinelli, 2013). It appears that individuals take this medial-lateral sway into account when determining what gaps are safely navigatable, and tend to use this trunk sway (and trunk sway variability) to gauge safe passage. It is therefore necessary to understand dynamic stability differences (action capability differences) between athletes and non-athletes to assess strategies for gap crossing.

No differences were identified between groups in ML COM variability during the approach, suggesting that athletes and non-athletes do not differ in their action capabilities on this task. Hackney & Cinelli (2013) reported differential navigation strategies between older and younger adults on a gap crossing task. Older adults were found to act more cautiously than younger adults by leaving more space between their shoulders and the obstacles. The authors concluded that this was a result of increased medial-lateral COM variability during the approach phase. Thus, older adults were accounting for the increased variability of their trunk segment when determining action strategies (Hackney & Cinelli, 2013). These results corroborate the lack of differences between athletes and non-athletes on navigational strategies. If both groups maintain similar dynamic stability, they are accounting for the same action capabilities, and thus will demonstrate similar navigational strategies (Franchak et al., 2012; Hackney & Cinelli, 2013).

4.5 Personal Space and Safety Margin

Safety margin can be described as an area of personal-space (Gerin-Lajoie et al., 2006; Hackney and Cinelli, 2013), or a bubble surrounding an individual in which no obstacle is allowed to enter. For example, when deviating around obstacles, participants leave a certain amount of space between the edge of their shoulder and the obstacle. It appears that in the current study non-athletes left marginally more space between their shoulder and the obstacles than athletes, but this difference was not found to be statistically significant (Figure 3.3). Previous research by Higuchi and his colleagues (2011) revealed that athletes specifically trained in gap crossing only demonstrated strategies in which they better perceived the size of their body for navigation while running. These authors found that rugby and football athletes left a smaller safety margin between their shoulders and the obstacles, by creating smaller, later-onset shoulder rotations when confined to navigate through a gap (Higuchi et al, 2011). As athletic related differences were only elicited when rugby and football athletes were running and not walking, these authors concluded that athletic related differences are highly context specific. Indeed, the lack of significance between our two groups may suggest similar specificity of training. This finding may also be a result of direction of deviation. Previous research has found that ML safety margin is smaller when participants deviate to their dominant (right) side (Gerin-Lajoie et al., 2006, 2008). Athletes may have tended to deviate to the right more often than non-athletes, which may have driven this effect (see Appendix E).

No significant differences were identified between the ML safety margins when participants deviated around gaps of 0.9 and 1.1 x SW. Therefore, regardless of obstacle distance, or gap widths, all participants were found to perform highly similar actions to maintain ML safety margins. These findings are in line with Hackney & Cinelli (2013), who found that both younger and older adults maintain consistent ML safety margin across all gap width conditions. Such findings suggest that individuals were not just deviating to a consistent point in space, but rather that possibly the lateral repulsion vectors emanating from the obstacles were consistent for all obstacle positions and therefore produced similar deviation magnitudes at TOP for all individuals (Fajen and Warren, 2003).

Participants appear to leave less space between their shoulders and obstacles as proximity of the obstacles to the starting location decreased (Figure 3.3). This trend however, was also not statistically significant. Yet, it must be noted that these findings are in line with those of Fajen & Warren (2003) who identified that peak deviation position decreased slightly with increased obstacle distance from the start. These authors also found that when the goal was located closer to the obstacles, participants tended to navigate toward the midline of the travel path to more efficiently achieve the goal (Fajen & Warren, 2003). In the current study, when the obstacles were located 7m from the start they in turn were located 3m from the goal. Our findings indicate that participants may have adopted one or both of the strategies identified by Fajen & Warren (2003) in order to maintain their trajectory closer to the midline of the travel path to more efficiently reach the goal with increased obstacle distance from the start. This result aligns with the hypothesis that the environmental features at the 7m location differentially affected behavioural dynamics compared to obstacles at the 3m and 5m locations. It can be concluded that this finding was not a factor of dynamic stability (action capabilities) as this did not differ between conditions. The current study included two obstacles, where Fajen & Warren (2003) only observed individuals' avoidance behaviour with one obstacle en route to a goal. Interestingly, the combination of two obstacles interacted in such a way to deter participants from choosing to navigate between smaller gap sizes at this obstacle location, even though this would have enabled them to more efficiently reach the goal. However, since participants were not allowed to pass through the gaps while rotating their shoulders, smaller gaps had to be avoided (deviate around) rather than passed through.

In the current study, no differences were identified between the AP safety margins of specifically trained athletes and non-athletes. However, AP safety margin was found to increase with increasing obstacle distance. AP safety margin was twice as great when participants avoided obstacles located 7m (safety margin = 2.4m) from the start, compared to those at 3m (1.2m) and AP safety margins for all three distances were statistically significantly different from each other (Figure 3.3). These trajectories may be a result of what each unique environment afforded. It would have been incredibly challenging to leave a safety margin of 2.4m when approaching obstacles at 3m, as participants would have had to make judgments based on perceptual information and initiate action strategies almost instantaneously. Instead, it appears they maintained their trajectory for 1.8m before initiating deviations around obstacles located 3m from the start. All participants continued to increase the distance travelled along the midline of the path, with increasing obstacle distance. This finding may suggest that the attractor point may not have been initially located at the goal for each condition. During the 3m condition, the attractor point may have been located in line with or just past the midpoint between the gap, resulting in participants getting closer to the obstacles before being repelled.

4.6 Action Strategy Conclusions

Athletes and non-athletes did not differ in their decision making for navigation on this task. These findings were a result of similar perceptual judgement strategies and similar dynamic stability between groups. These findings are similar to those of Higuchi et al. (2011) who identified that athletic related differences on navigation were only found while participants were running, and not while walking. Higuchi et al. (2011) attributed this to the task specificity of running while navigating. However, as obstacle distance remained the same between the walking and running conditions in the experiment conducted by Higuchi et al. (2011), athletes may have performed sport-specific navigational strategies due to the fact that decisions had to be made more rapidly. Gérin-Lajoie et al. (2007) found that under increased time constraints, athletes navigated through a maze more efficiently than non-athletes. These results suggest that athletes demonstrate more efficient navigation strategies under temporal constraints and/or while running. As the current study found no group differences in action strategy at the 3m location, we suggest that athletic-related differences in navigational strategies are due to running, and not time. Future research is required to confirm this finding by assessing athletic related differences in navigational strategies under increased time constraints or under the constraints of moving obstacles.

4.7 Gaze Strategies

Although athletes and non-athletes did not differ in their navigational strategies, nor in their dynamic stability, athletes were found to make fewer, longer fixations compared to non-athletes (Figures 3.4 and 3.5). Assessing visual sampling strategies provides valuable insights into determining what individuals were overtly attending to, while they performed the experimental task. Carpenter (1988) noted fixations of 100ms or more are indicative of overt, conscious attention being placed on the object of the fixation point. Similarly, fixation durations are thought to reflect the amount of time required to process visual information (Cinelli et al., 2009). Mann and colleagues (2007) provided an excellent assessment of literature assessing visual sampling in different athletic populations through a meta-analysis. The authors conducted their analysis as they believed there was a lack of ecological validity between the variable experimental constructs and populations in previous research. However, the authors found similar conclusions across all paradigms: elite-level athletes used fewer, longer visual fixations to perform more successful action strategies related to their sport. Mann et al. (2007) described such gaze strategies as more efficient, as compared to strategies that include more variable scanning behaviours (making more fixations of shorter durations). This finding has been interpreted as experts' ability to obtain more salient visual information from each fixation compared to non-experts (Mann et al., 2007; Vickers, 2007). It was originally hypothesized that similar gaze strategies would be observed in our athlete population, compared to our non-athletes who would demonstrate more fixations of shorter duration. Given the findings of multiple studies conducted by Vickers and her colleagues, it was also hypothesized that athletes would demonstrate Quiet Eye, where non-athletes would not. Vickers (2007) describes quiet eye as the last, long visual fixation before experts perform a skilled motor task. Through similar assessment of fixations of long duration being more efficient, Vickers has found more successful action strategies when athletes perform Quiet Eye (Vickers, 2007).

Athletes in the current study were found to make fewer fixations of longer duration across all obstacle conditions compared to non-athletes. These findings indicate that athletes are required to visually sample the environment with a smaller number of fixations of longer duration than non-athletes. Such findings align with numerous findings comparing fixation strategies of elite and expert level athletes to novices (Causer et al., 2010; Mann et al. 2007; Vickers, 1992, 2007; Williams et al., 2002). Athletes in the current study were also found to make use of the Quiet Eye as they were found to have longer final fixations prior to passing the obstacles compared to non-athletes. This finding is not surprising as numerous studies have evidenced Quiet Eye in specifically-trained and elite athletic populations (Vickers, 2006; Vickers, 2007; Martell & Vickers, 2004; Panchuk & Vickers, 2006; Vickers, 2009). Although these previous studies have found sport-specific action strategies that emerged from gaze strategies with fewer, longer fixations, the current study identified significant differences in gaze strategies with no differences in action strategies. These results may suggest that athletes and non-athletes were investing differential amounts of overt attention during the task in the current study, to perform similar navigation strategies. As non-athletes were attending to more numerous fixation points, perhaps they were investing more conscious attention to the task. As such, it is possible that within these parameters, non-athletes were able to perform actions similar to athletes, but with a greater attentional cost. Such a relationship must be assessed, likely through the use of a dual-task paradigm, to confirm this conclusion.

Numerous authors have concluded that a greater number of fixations of shorter duration evidence a less effective gaze strategy, compared to those strategies of fewer, longer fixations. These authors have found that fewer, longer fixations correlate with more successful action strategies related to sport (Vickers, 2002; Williams et al., 1993). Within this definition, the findings of the current study suggest that athletes demonstrated more effective gaze strategies than non-athletes. However, athletes were found to have significantly more variable fixation durations compared to non-athletes. This finding may be due to the fact that the athletes in the current study were comprised of athletes specifically trained in different sports, which could have resulted in variable visual fixation strategies. As no study has yet to evidence gaze strategies between sports, few conclusions can be drawn as to this potential relationship. However, in their meta-analysis, Mann and colleagues (2007) noted that fixation durations are similar across sports, with experts seeking more information-dense aspects of the visual scene. It is also possible that athletes attached different attentional values onto objects within the environment such that those objects that required more attention resulted in longer fixations whereas non-athletes attached equal weight onto all the objects in the environment (Cave & Wolfe, 1990). It is important to note that no interactions were identified between participant group and condition (obstacle distance or gap size), suggesting that differences in fixation durations between groups is not a result of increasing fixation duration when interacting with obstacles creating different sized gaps or at different locations.

4.8 Gaze Strategies Relevant to Travel Path

Gaze strategies were assessed between navigational strategies to identify whether participants were using an *a priori* or on-line visual control strategy to perform adaptive locomotion. If similar fixation strategies were observed between conditions of obstacle distance and gap width, it could be concluded that participants were employing a predicative, *a priori* control strategy. No differences were observed when assessing gaze fixation duration between conditions (obstacle distance nor gap width), nor were differences observed number of fixations between gap widths. This means that participants sampled information similarly regardless of whether obstacles created gap widths very close to, or much larger than shoulder width. These findings differ from those of Cinelli, Patla, & Allard (2009). Their study examined gaze fixation strategies of young adults attempting to navigate through a moving doorway (gap). The authors identified significantly longer fixation durations during the approach phase, when the condition was difficult to predict (asymmetrical door movement) compared to easy to predict (symmetrical door movement). Cinelli et al. (2009) concluded that significantly longer fixations under the asymmetric door condition were required due to task complexity, where participants needed more information and/ or information took longer to process, compared to the symmetric task. Continuing with this thought process, the stationary obstacles present in the current study pose a greatly reduced perception-action integration challenge. Using perception to accurately guide actions while interacting with a stationary gap of 1.1 x SW may be similarly as straightforward as interacting with a stationary gap of 1.7 x SW, and therefore resulted in similar fixation strategies. It is possible that participants were able to accurately judge from their first fixation whether or not an aperture was passable. Following this first fixation, all other fixations were directed towards the salient features of the environment which were consistent across all trials. Therefore, it would be expected that gaze behaviours would only differ in situations in which a change to the environment (Cinelli et al., 2009) or participants' action capabilities (Higuchi, Cinelli, and Patla, 2010) occurred. As such, it appears that participants used an *a priori* control strategy regardless of gap width during situations in which the environment remains static.

However, although fixation duration did not differ between obstacle distances, number of fixations did. Specifically, as obstacle distance from the start increased, so too did number of fixations (Figure 3.4). This finding is not surprising given the increased amount of time required to approach the gap. Yet, it appears that participants did not use this visual information to differentially interact with the obstacles, as the only significant finding in action strategies was an increase in AP safety margin with increased obstacle distance. Therefore, participants likely did not rely on an obstacle expansion threshold to initiate a change in travel path (Cinelli and Patla, 2007). Even though this finding has been attributed to what the obstacle-goal proximity afforded (Fajen & Warren, 2003), differential gaze strategies must be noted as potentially influencing this effect.

Navigational strategies (travel path choices) were found to be less consistent in this study compared to previous findings (Warren & Whang, 1987; Hackney & Cinelli, 2013), particularly when participants interacted with gaps equivalent to 0.9 and 1.1 x SW. Because of this, it is important to understand what may have caused the increased variability observed in this study. Through examination of gaze strategies, we can obtain a better understanding of what may have resulted in this difference. Ad hoc, it was hypothesized that if participants were highly variable under similar environmental constraints, they were likely adopting an on-line visual control strategy as an *a priori* strategy would likely result in highly consistent strategies (Fajen & Warren, 2003). Gaze strategies were examined through a comparison of trials that resulted in different action strategies (i.e. deviate around or walk through the gap created by the two obstacles). Decision making variability was not found to be related to number of fixations, nor was decision making variability found to correlate with fixation duration. These results suggest that participants visually sample the environment similarly, regardless of how consistently they performed action strategies. As such, participants were found to use an adaptive, *a priori* control strategy to gauge safe navigation.

However, participants were found to make significantly longer fixations when approaching obstacles that created gaps that they chose to navigate through (Figure 3.6). This may be a result of participants attempting to maintain a safe trajectory between the obstacles. Cinelli et al. (2009) found that participants adopted a look-ahead strategy when navigating through moving gaps. The authors suggested that this was likely a result of attempting to keep both obstacles within the field of view while passing between them. Using their peripheral vision, these participants were able to continue to identify the location of both obstacles while they passed between them (Cinelli et al., 2009). Although the current study posed less of a navigational threat, it is likely our participants adopted a similar fixation tendency when navigating between the obstacles through the gap.

4.9 Conclusions

Athletes and non-athletes demonstrated similar action strategies across all obstacle conditions. Further analyses revealed that this was a result of similar dynamic stability and perceptual judgements between groups. Visual fixation strategies were not found to differ between conditions, suggesting that both participant groups adopted an *a priori* visual control strategy for navigation on this task. However, athletes were found to make fewer, longer visual fixations than non-athletes. These findings suggest that non-athletes may be directing more conscious attention to the task, thus enabling them to perform at the same level of accuracy as athletes. Athletes were found to make fewer, longer fixations than non-athletes, suggesting that they demonstrate different perception-action integration strategies than their untrained counterparts. These findings suggest that athletes demonstrate more efficient gaze strategies (as per Mann et al., 2007; Vickers, 2007), but did so in the absence of sport-specific action strategies. Previous studies have identified that such gaze fixation strategies are predictors of more effective sport-specific action strategies (Mann et al, 2007), but this was not found to be the case in the current paradigm.

As the current experimental task identified athletic differences in gaze strategies, but not in navigational strategies, it is likely that this aspect of the task was not the most effective means to identify athletic related differences in navigation strategies. In future, it is important to identify whether navigational strategies differ between athletes and non-athletes when examining their behaviours when interacting with gap sizes that are more challenging (i.e. gap widths in increments of .1 x SW) or decision making conditions that are more challenging (i.e. moving obstacles, running, decreased obstacle distance). Perhaps with more challenging conditions, and those more context-specific to sport, athletic related navigational strategies will be identified.

5. Results: Study 2

The purpose of this study was to identify whether athletes with PCS demonstrate perception-action integration deficits compared to uninjured athletes. More specifically, this analysis will focus on visuomotor control, as previous research has identified concussion-related deficits in visual control of movement (Baker & Cinelli, 2013;

Locklin et al., 2010). Study 1 placed this experimental task within the fundamental research on perception-action integration and adaptive locomotion. Study 2 will build on these concepts through assessment of the clinical application of the current experimental task.

5.1 Travel Path

ML COM position at the time of passing the obstacles (TOP) was identified. This value was determined through assessing the distance from the midline of the travel path. Small values (close to 0cm) indicated participants chose to walk through the gap between the obstacles. Large values (>30cm) indicated a change in travel path, or a deviation around the obstacles. Results did not identify group differences in ML COM at TOP ($\bar{x}_{PCS}$=24.52±31.26; $\bar{x}_{Athletes}$=19.96±28.72). However, a main effect of gap width was identified ($F_{(2.44,48.83)}=47.08$, $p<.001$, $\beta>.99$). Post hoc analyses revealed that ML COM position at the time of passing the obstacles was significantly smaller when participants interacted with gaps of 1.7 x SW ($\bar{X}$=4.69cm) compared to gaps of 0.9 and 1.1 x SW ($\bar{X}$=58.76, and 34.90cm respectively), indicating that participants chose to deviate around gaps equal to or less than 1.1 x SW, and navigate through gaps equal to or greater than 1.3 x SW. No other main effects or interactions were identified (Figure 5.1, 5.2).

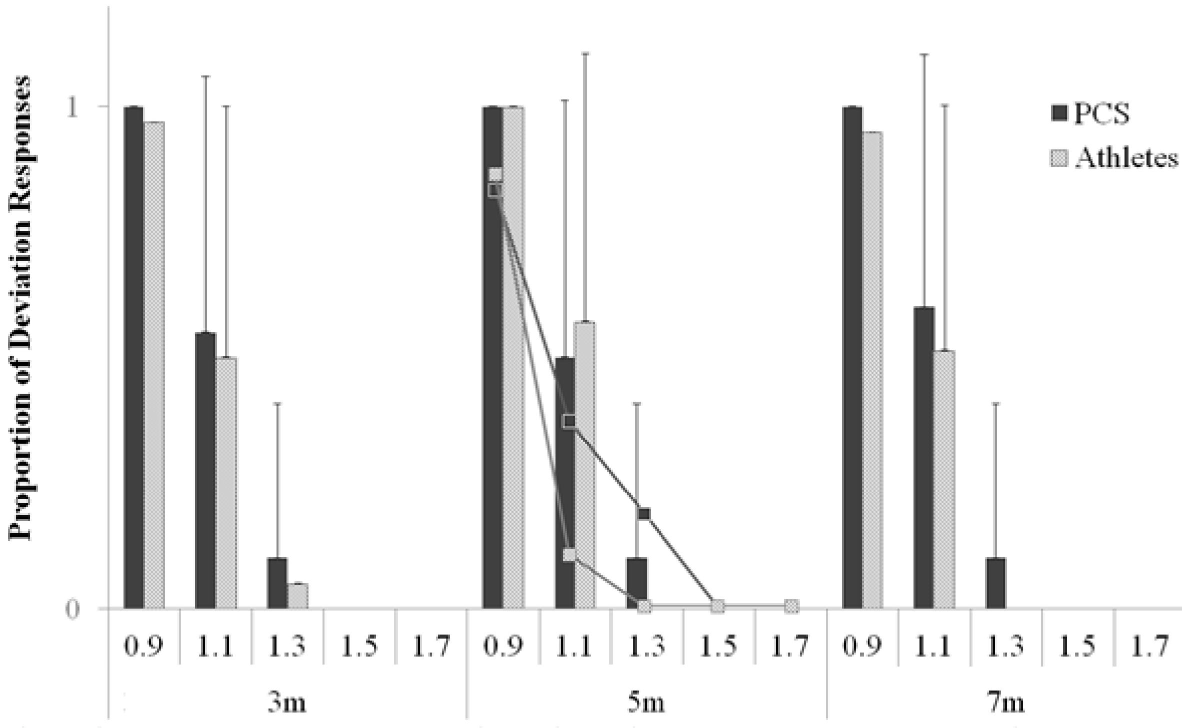

Figure 5.1: Proportion of trials where participants navigated around the obstacles are depicted. Proportion of responses where participants did not perceive they could safely navigate through the graph is overlaid. Individuals with PCS perceived safe passage through gaps of 1.3 x SW or greater, where athletes perceived safe passage through gaps of 1.1x SW or greater.

5.1.1 Travel Path Variability

ML COM variability (standard deviation) at the time of passing the obstacles was compared between groups to assess variability in decision-making between groups, gap widths, and obstacle conditions. It was hypothesized that if individuals with PCS were suffering from visuomotor impairment, they would demonstrate more variable decision-making strategies. No support was obtained for this hypothesis as no effect was identified between groups ($\bar{x}_{athletes}$=5.68±12.23; $\bar{x}_{PCS}$=5.73±12.98). Results revealed a main effect of gap width ($F_{(2.11,29.58)}$=4.96, p<.05, β=.78). Post hoc analyses revealed that participants were significantly more variable when interacting with obstacles that created gaps of 0.9 x SW ($\bar{x}$=6.35) compared to gaps of 1.5 and 1.7 x SW ($\bar{x}$=2.52 and 1.39 respectively). No other main effects or interactions were identified (Figure 5.2).

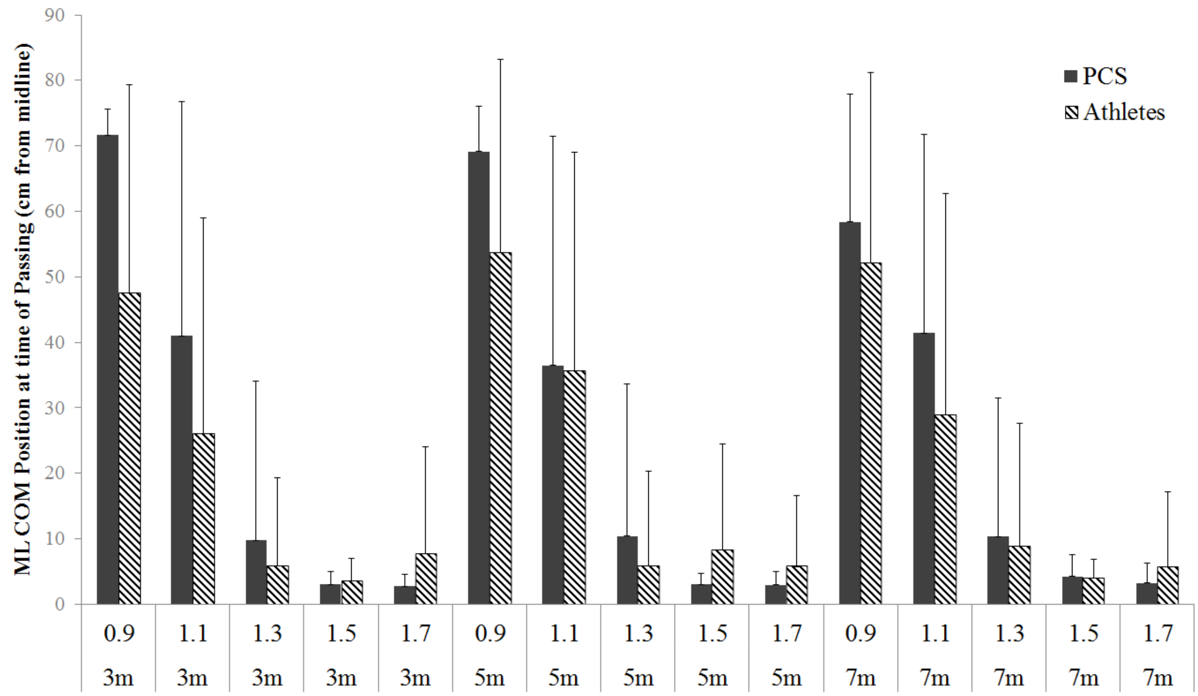

Figure 5.2: ML COM position at the time of passing the obstacles is depicted. Large values indicate a change in travel path and small values indicate participants chose to navigate through the gap created by the two obstacles. A main effect of gap width was identified where MLCOM position was significantly greater when participants passed obstacles that created gaps of 0.9 and 1.1 x SW, indicating that both groups tended to pass through gaps that were 1.3 x SW or greater (p<.01). No effect of obstacle distance was identified, nor were any group or condition differences observed in travel path variability.

5.2 Perceptual Judgement

As navigational strategies did not differ between groups, perceptual judgement strategies were assessed to identify whether participants were similarly judging their body size for navigation, regardless of whether they were suffering from PCS. If groups were to differ on this measure, with athletes who were not concussed perceiving safe passage through gaps closer to their body size, it could be concluded that the non-concussed athletes could better perceive their shoulder width for more accurate navigation. Participants were asked to judge as to whether they believed they could safely pass between a gap (0.9-1.7 x SW) placed 5m from the start. "Yes" or "No" responses were recorded without participants having physically passed through the gap. Group differences were assessed by identifying the smallest gap width that participants identified as safely passable (two "yes" responses). A t-test was conducted comparing the smallest gap width participants deemed safely passable demonstrating a significant difference between the groups. Specifically, results revealed that non-concussed athletes perceived they could safely pass through gaps that were equal to or larger than 1.1 x SW ($\bar{x}$=1.10±.12) where individuals with PCS perceived they could safely pass through gaps equal to or larger than 1.3 x SW ($\bar{x}$=1.28±.22; $t_{(13.38)}$=2.31, p=.024) (Figure 5.1).

5.3 Dynamic Stability

It was hypothesized that individuals with PCS would likely demonstrate greater ML COM variability (standard deviation) during the approach, and that this variability would increase with increasing obstacle distance, particularly compared to the athlete group, who would maintain low ML COM variability. No significant differences were observed between groups. Results identified a trend of gap width ($F_{(1.84,29.43)}$=6.78, p=.013, β=.87). Post hoc analyses revealed that participants were more variable when approaching gaps of 0.9 x SW ($\bar{x}$=4.87) compared to most other gap widths ($\bar{x}$=3.16, 2.14, 2.19 for gaps of 1.1, 1.3, and 1.7 x SW respectively; the pairwise comparison between gaps of 0.9 x SW and 1.5 x SW was not significant).

5.4 Related Behaviours

5.4.1 Speed

Speed was assessed both during the approach phase and at the time of passing the obstacles. It was hypothesized that during the approach phase individuals with PCS would walk slower than athletes to allow themselves more time to make accurate decisions, particularly for more perceptually challenging gap widths (i.e. those close to SW). However, only a trend of obstacle distance was identified ($F_{(1.19,21.43)}$=5.66, p=.022, β=.67), where participants walked faster toward obstacles located 7m from the start ($\bar{x}$=133.51cm/s) compared to those 3m from the start ($\bar{x}$=126.09cm/s). No significant differences in gait speed were observed between the 3m and 5m or 5m and 7m locations as participants walked at a pace between those of 3m and 7m toward obstacles located 5m from the start ($\bar{x}$=130.93cm/s). There were no other significant effects.

It was hypothesized that when passing the obstacles that created a greater perceptual challenge (i.e. those similar to SW), participants would decrease their speed, compared to other, less challenging gap widths. Neither significant interactions nor main effects were identified. The variability (standard deviation) of speed at the time of passing the obstacles was also assessed. A main effect of obstacle distance was identified

($F_{(1.07,14.99)}$=16.81, p<.001, β=.98). Post hoc analyses revealed that participants had significantly more variable gait speed when interacting with obstacles located 7m from the start ($\bar{x}$=27.95) compared to those located 3m ($\bar{x}$=7.69, p<.01) and 5m from the start ($\bar{x}$=6.06, p<.001). Individuals with PCS ($\bar{x}$=17.13) demonstrated more variable gait speed than their non-concussed counterparts ($\bar{x}$=10.66), but this difference was not significant ($F_{(1,14)}$=3.21, p=.095, β=.39). No other effects or interactions were identified.

5.4.2 Safety Margin

ML safety margin- the distance between the outer edge of the obstacle and the most lateral aspect of the participant's closer shoulder- was calculated for trials where participants chose to deviate around, rather than walk through the obstacles. No significant main-effects were identified, nor were interactions observed.

AP safety margin was calculated for trials when participants chose to deviate around the obstacles, instead of passing through the gap. AP safety margin was determined by identifying AP COM position when each participant had made a significant path deviation (AP COM position when ML COM fell outside of and remained ±2 SD from the straight through travel path). Results identified a main effect of obstacle distance ($F_{(2,34)}$=49.65, p<.001, β>.99), where AP safety margin increased with increased obstacle distance. Participants were found to leave a significantly greater AP safety margin when approaching obstacles located 7m from the start ($\bar{x}$=219.90cm) compared to those at 5m or 3m ($\bar{x}$=182.13, 121.74cm respectively; p<.001). Similarly, participants left a significantly larger AP safety margin when approaching obstacles that were 5m from the start, compared to those 3m from the start (p<.01). Groups were not found to differ on this metric, nor were different AP safety margins identified between gap widths.

5.5 Gaze Strategies

It was hypothesized that athletes with PCS would perform a greater number of fixations, of shorter duration, than non-concussed athletes. This is due to the fact that one cardinal symptom following a concussion is visuomotor deficit (Baker and Cinelli, 2014; Lockin et al., 2013). As such, it was believed that if individuals with PCS were demonstrating visuomotor deficits, this would be evidenced through an inability to effectively fixate salient information. Further, as we did not observe any differences between groups on any measure of kinematics, it was hypothesized that individuals with PCS may need to pay more overt attention to the task, whereby increasing the number of fixations they made, to gain more overt visual information to accurately perform the task.

No group differences were identified on average fixation duration, nor were any effects of obstacle distance or gap width identified. Similar results were identified for analysis of length of final fixation, with no group differences or main effects of conditions identified (Figures 5.3 and 5.4).

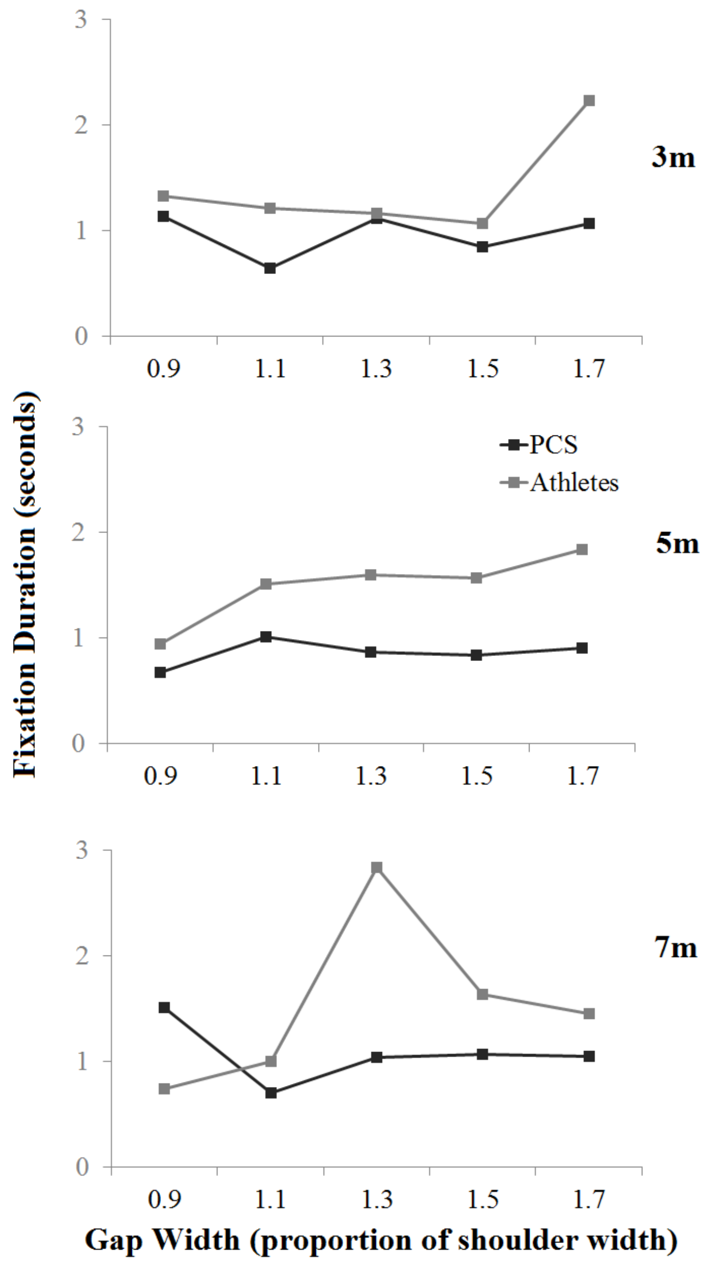

Figure 5.3: Average fixation duration for each condition. No differences were observed between groups.

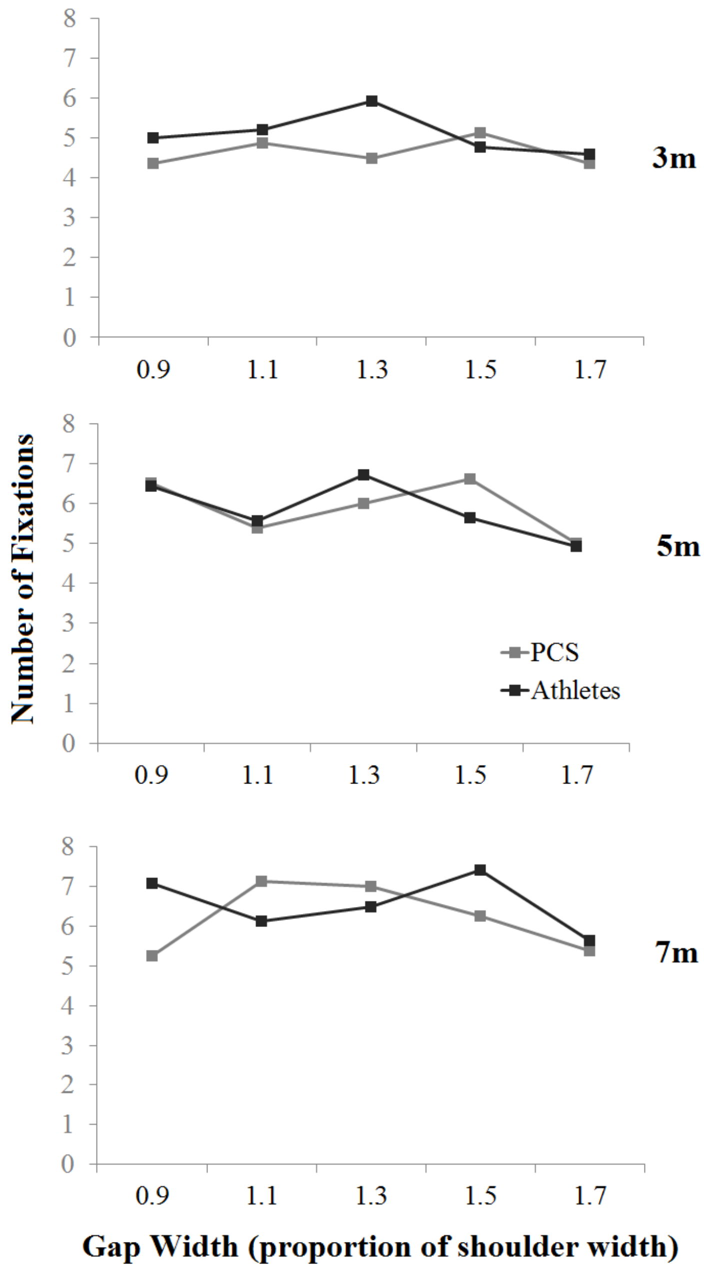

Figure 5.4: Average number of fixations for each condition. Number of fixations was found to increase with increasing obstacle distance (p<.05). No group differences were identified.

6. Discussion: Study 2

Several studies have found that previously concussed athletes demonstrate deficits in visuomotor integration (Baker & Cinelli, 2014; Locklin et al., 2013; Slobounov et al., 2006). Such deficits have been found to resolve within 1 month post-concussion in static stability paradigms (Slobounov et al. 2006), but were found to persist for an extended time period when dynamic stability and a more complex visuomotor integration task were administered (Baker & Cinelli, 2014). Baker & Cinelli (2014) found visuomotor deficits of concussion persist up to two months post-injury. However, most studies assessing visuomotor deficits post-concussion have been performed on asymptomatic individuals and similar deficits had yet to be studied in the PCS population. Thus, the current study sought to understand whether individuals with post-concussion syndrome (PCS) demonstrated visuomotor integration deficits, so that rehabilitative processes could possibly focus on recovering this function.

The purpose of this study was to determine if visuomotor deficits persisted with persisting physical symptoms of concussion in PCS. It was hypothesized that athletes with PCS would demonstrate more variable, cautious action strategies compared to non-concussed athletes due to previous findings of dynamic stability and visuomotor deficits of concussion (Baker & Cinelli, 2013; Slobounov et al., 2006), as well as psychological factors of PCS that may reduce confidence and increase anxiety during this task (Broshek et al., 2015; Leddy et al., 2007). It was also hypothesized that athletes with PCS would demonstrate impaired visual fixation strategies as Heitger and colleagues (2009) identified profuse visual motor deficits in individuals with PCS. This study employed a dynamic, visuomotor integration task to assess decision making between individuals experiencing PCS and a non-concussed athletic control group. Individuals with PCS were found to make similar navigational decisions to their uninjured counterparts. Similarly, individuals with PCS did not differ from athletes in their dynamic stability, nor were their visual search strategies different. These findings suggest that since the individuals with PCS were not different from the non-concussed athletes, they were likely not suffering from visuomotor deficits. Such findings are relevant to assisting rehabilitative practices, including the potential for these individuals to participate in increasingly more activities of daily living.

6.1 Travel Path

Travel path choices were not found to differ between individuals with PCS and uninjured athletes (Figure 5.2). Both groups were found to navigate through gaps that were greater than or equal to 1.3 x SW. These results reveal that individuals with PCS and non-concussed athletes use body-scaled information to perform similar navigation strategies. These findings are similar to previously reported gap crossing tasks where younger adults were found to walk straight through gaps equal to or greater than 1.3 x SW (Franchak et al., 2012; Hackney et al., 2013; Higuchi et al., 2011; Warren & Whang, 1987). As such, it could be assumed that both of our participant groups, including individuals with PCS, act similarly to numerous groups of non-athletes; the PCS group were also not found to act cautiously like older adults (Hackney & Cinelli, 2013).

Baker & Cinelli (2014) identified that decision-making variability was vastly increased in the group of previously concussed athletes they assessed. However, athletes and individuals with PCS in the current study demonstrated similar decision-making variability as their non-concussed counterparts (Figure 5.2). Previous research on younger adults has identified that they use highly consistent navigational strategies (Hackney et al., 2013). Therefore, as the individuals with PCS in this study did not demonstrate variable action strategies, but instead navigated with similar consistency to younger adults, it can be concluded that these individuals were not suffering from visuomotor integration deficits that would affect performance on this task.

6.2 Perceptual Judgement

The perceptual judgment task was the only task that revealed group differences (Figure 5.1). Athletes were found to perceive safe navigation through gaps equal to or greater than 1.1 x SW, where individuals with PCS were found to perceive safe navigation through gaps greater than or equal to 1.3 x SW (Figure 5.2). From this, it could be suggested that individuals with PCS were making more cautious perceptual judgements, which may be attributed to poorer dynamic stability (Hackney & Cinelli, 2013) or anxiety given their current diagnosis (Broshek et al., 2015). Hackney & Cinelli (2013) found that when stationary, older adults perceived safe passage through gaps at the same aperture to shoulder width ratio as younger adults (A/S=1.4). However, when asked to make perceptual judgements while in a dynamic state (walking perceptual judgement), older adults perceived that gaps greater than or equal to 1.6 x SW were passable. Older adults were found to have more variable medial-lateral COM sway while walking, which they took into account when perceiving safe navigation (Hackney & Cinelli, 2013). The authors concluded that older adults were assimilating their dynamic stability during the approach phase in how they determined safe navigation. This is in line with the idea that individuals rely on behavioural dynamics to guide their actions (Warren, 2006). Previously concussed individuals have been identified as having poor dynamic stability, with highly variable COM sway (Slobounov et al., 2006; McFayden et al., 2009; Powers, Kalmar, & Cinelli, 2013; Baker & Cinelli, 2014). Therefore, it may have been assumed that individuals with PCS were assimilating their poorer dynamic stability into perception-action integration, but this however, was not the case (see next section for details). In the context of the previous findings regarding navigation strategies, these results may, in turn, suggest that individuals with PCS demonstrate more consistency between their perceptual judgements and navigation strategies compared to their uninjured counterparts. Hackney & Cinelli (2013) found a similarly high consistency between action strategies of non-concussed younger adults, but not older adults. As such, individuals with PCS are likely demonstrating visuomotor integration strategies typical of a non-concussed population. The current study found that only the perceptual judgments of individuals with PCS mapped on to their actions; the non-concussed group was more "risky" during their perception. Therefore, it could be argued that if it is typical for non-concussed individuals to demonstrate a disconnect between the perceptions of action capabilities and the act of completing a goal-directed task with non-concussed athletes, then the PCS group may be experiencing visuomotor deficits.

6.3 Dynamic Stability

Catena et al. (2009) identified dynamic stability deficits in previously concussed individuals up to 28 days post-injury. The authors identified that previously concussed individuals demonstrated reduced ML COM variability, and that these results were most marked during obstacle avoidance after 14 days post-injury (Catena et al., 2009). In the current study, dynamic stability during the approach phase was assessed using a calculation of each participant's medial-lateral COM variability. It was believed that the individuals with PCS would have greater instability (i.e., greater variability) and this would lead to them requiring larger gaps to pass through (Hackney & Cinelli, 2013). Since the individuals with PCS did not act differently than the non-concussed athletes, it was not surprising that there was no difference between the groups' medial-lateral COM variability during the approach phase. These results suggest that although individuals with PCS are still experiencing physical symptoms of concussion, they demonstrate similar dynamic stability to non-concussed athletes.

This finding is not consistent throughout the literature. Catena, van Donkelaar, & Chou (2011) identified that previously concussed individuals appeared to have recovered balance by 28 days post-injury. However, these individuals performed significantly worse on a concurrent dual-task, suggesting that previously concussed individuals are still suffering from cognitive deficits 28 days post-injury, but are prioritizing balance over a secondary, cognitive task. Both Fait et al., (2013) and Baker & Cinelli (2014) identified visuomotor integration deficits during obstacle avoidance tasks up to 30 days (and beyond) in previously concussed populations. However, as individuals with PCS in the current study appear to have no dynamic stability or visuomotor integration deficits while walking, it is likely that they have recovered the ability to perform the two tasks (balance and choice navigation) concurrently. As such, it appears that these individuals with PCS may have adequately recovered to perform more complex or difficult visuomotor integration tasks. The paradigm presented by Hackney, Zakoor, & Cinelli (2014), comparing navigation strategies while running at a self-selected pace, may be optimal to assess these outcomes in a more demanding environment.

6.4 Personal Space and Safety Margin

Safety margin is a measure of the “buffer zone” that individuals require around their bodies when avoiding contact with other objects (Gerin-Lajoie et al., 2005). It was believed that the individuals with PCS would require larger safety margins, similar to older adults, because they were expected to have less confidence in their actions (Gerin-Lajoie et al., 2006). However, group differences were not identified on either the AP or ML safety margins. AP safety margin defines the point at which participants had deviated from a straight path (Hackney et al., 2013). As groups did not differ on this metric, nor gait speed, it can be understood that both athletes and individuals with PCS were processing information to guide their actions similarly.

ML safety margin demonstrates the amount of space that individual feel comfortable leaving between themselves and obstacles when avoiding them. This value can be affected by dynamic stability (Hackney and Cinelli, 2013), path trajectory (Fajen and Warren, 2003), or the level of threat/uncertainty of an object (Gerin-Lajoie et al., 2005). It was believed that individuals with PCS would require a larger ML safety margin due to one or more of the above reasons. However, no differences were observed in ML safety margin between the groups, suggesting that there is no difference in the amount of space perceived to be required between the two groups and the obstacles at the time of passing the obstacles. Research assessing previously concussed individuals has identified variable clearance margins and more conservative stepping strategies when avoiding planar obstacles (Chou et al., 2004; Martini et al., 2011). Martini et al. (2011) conclude that they identified kinematic differences in stepping strategies, when interacting with an obstacle, in individuals who had sustained a concussion an average of 6 years prior to study participation. It is possible that the reason the current study identified no differences in kinematics (safety margin, variability, and dynamic stability) was because more precise kinematic measures (i.e. time in double support) may be required to more acutely identify such differences. Another potential difference may be related to athletic involvement. Martini and colleagues (2011) do not specify participant demographics beyond history of concussion and physical parameters of participants (gender, weight, height). Therefore, the previous study may have potential confounds that were not identified from lack of detailed participant history. Conversely, the current study participants may have adapted to their PCS because of some factor related to their athletic involvement. Individuals with PCS in the current do not appear to have deficits in ML COM variability that would affect safety margin or navigation strategies. Further research is required to conclude why the current study identified no differences between a group of athletes with PCS and their non-concussed counterparts, where other research has identified gait deficits in a group of previously concussed individuals who have seemingly recovered (Martini et al., 2011).

Although previous literature has identified visuomotor deficits (Baker & Cinelli, 2014; Lockin et al., 2013; Slobounov et al., 2006; Slobounov et al., 2008) and dynamic stability deficits (Baker & Cinelli, 2014; Chou et al., 2004; Howell et al., 2013; McFayden et al., 2011; Slobounov et al., 2006) following a concussion, neither of these differences were identified in the current study. Perhaps these findings are a factor of time post injury, as most of the previous literature has assessed previously concussed individuals 30 days or less post-concussion. Indeed, it appears that studies assessing concussion recovery after 100 days have provided inconclusive evidence. Baker and Cinelli (2014) found no differences between previously concussed individuals and their non-concussed counterparts after two months post-injury. However, Martini et al. (2011) identified differential gait kinematics up to 6 years post-concussion. In the current study, we did not identify kinematic differences between individuals with PCS and uninjured athletes. At this time, we can conclude, based on our population, that even though individuals with PCS still experience concussion symptoms, it appears that they have recovered their dynamic stability and visuomotor integration capabilities. However, this is not in line with previous research (Martini et al., 2011) and thus, must be investigated further. Future research should assess visuomotor integration in individuals with PCS with more precise gait measures to better quantify whether or not dynamic visuomotor deficits persist in the population.

6.5 Gaze Strategies

Previous research has identified that fewer, longer fixations are indicative of a more successful visual search strategy, as fewer, longer fixations have been found to correlate with more successful action outputs related to sport (Vickers, 2007; Mann et al., 2007). Further, evidence of the Quiet Eye has been associated with more accurate motor performance, specifically related to athletes with sport-specific training (Vickers, 2007). Murray and colleagues (2014) identified oculomotor deficits in individuals with a recent history of concussion (within 3 days post-injury). These authors assessed visual fixation stability and balance during a Wii balance board task. Individuals with recent history of concussion were found to make more fixations, with less ability to fixate a central target. Further, inefficient saccadic eye movements were identified in a cohort of individuals with PCS (Heitger et al., 2009). Since visuomotor deficits are a cardinal symptom post-concussion (Lockin et al., 2013), it was hypothesized that individuals with PCS would demonstrate a greater number of fixations of shorter duration when completing the current experimental task, compared to non-concussed athletes.

The findings from the current study indicated that individuals with PCS made a similar number of fixations, of similar duration, compared to uninjured athletes (Figure 5.4 and 5.5). Further, both non-concussed athletes and individuals with PCS made similarly long final fixations (Quiet Eye; Vickers, 2007). In their review of the literature, Mann and colleagues (2007) found consistent evidence of athletes performing fewer fixations, of longer duration compared to novice, or untrained athletes. These findings were correlated with excellent motor performance on sport-specific tasks. These results suggest that athletes with PCS performing similar numbers and durations of fixations as non-concussed athletes.

Since number of fixations and durations were not different between the two groups in the current study, it could mean that any visuomotor deficits are occurring in more motor aspects than perceptual aspects of the visual system (Heitger et al., 2009). Heitger and colleagues (2009) found that individuals with PCS demonstrated more variable ability to saccade to a target and poorer visuospatial processing compared to matched controls. Perhaps measuring high-frequency eye movements and/or the differing lengths of recovery between the previous study (Heitger et al., 2009) and the current study account for such differences. Heitger and colleagues (2009) assessed individuals with PCS an average of 140 days post-concussion, where the current study assessed individuals with PCS an average of 415 days post-concussion. It is quite likely that given the differential timeframes of the two studies, the current study participants were able to recover visual function more than those of Heitger et al. (2009). Additionally, the current study assessed visual fixations of a small subset of individuals. Further research attempting to evidence the recovery of visual function in individuals with PCS should assess high-frequency eye movements as well as a large range in time post-concussion in individuals with PCS.

Previous research has identified that a greater number of visual fixations likely identify the necessity of increased overt attention to the task. Cinelli and colleagues (2009) identified that participants made more fixations when required to complete a more complex gap crossing task. In the context of current findings, these results suggest that individuals with PCS do not require more overt attention than non-concussed athletes to accurately and safely perform this task. These findings suggest that individuals with PCS in the current study were equally as able to perform visuomotor integration task as specifically trained athletes.

6.6 Conclusions

Overall, the individuals with PCS in the current study displayed similar navigational strategies, possessed similar dynamic stability, and produced similar gaze strategies to non-concussed athletes. Based on these findings, it can be concluded that these individuals do not possess any visuomotor deficits as could be detected by this task. Perhaps if the experimental conditions were more challenging (i.e. gap sizes in increments of 0.1xSW, moving obstacles, less time to make decisions), perception-action integration deficits of PCS would have been identified. As more research is required on this PCS population, it is also potentially possible that their visuomotor deficits recover more rapidly than physical symptoms abate and/or these individuals have adapted to their injury to effectively integrate perception and action. If this is the case, certain activities of daily living requiring accurate visuomotor integration, that may have been previously considered as inappropriate for this population, should be re-evaluated.

6.7 Future Directions

Several studies have described the relationship between mood disorders and PCS (Broshek et al., 2015; Corwin et al., 2014; Silver, 2014). Exercise has been found to aid in the reduction of symptoms of anxiety, stress, and numerous other mental disorders (Dietrch & McDaniel, 2004; Esch et al., 2002; Stroth et al., 2009; van Praag, 2008). Other studies suggest an improvement in individuals with PCS associated with exercise. Participants reported a decrease in physical symptoms and a marked increase in mood-related symptoms (i.e. reduced anxiety) (Leddy et al., 2007; 2010; 2013). However, there are limitations to the amount and type of exercise individuals with PCS are recommended to participate in. The current standard of care is to ensure that individuals with PCS exercise at a level below symptom exacerbation (i.e. they do not exceed their exercise tolerance) (Leddy et al., 2010). As such, most of the literature concerning exercise and PCS has limited to stationary cycling (Leddy et al., 2007; 2010; 2013). Yet, outdoor activities have also been found to have a significantly positive effect on mood disorders (Barton, Griffin, & Pretty, 2012; Hahn et al., 2011), including the reduction of perceived stress, anxiety, and marked improvement in sleep regularity (Vella, Milligan, & Bennett, 2013); all of these studies have found significant positive effects of outdoor activity for symptoms of PCS. Barton and colleagues (2012) recommend the pairing of outdoor activity and exercise to further enhance the positive effects each therapy has separately. Given these findings, it could likely be particularly beneficial for the PCS population to exercise outdoors (i.e. cycling in a park). With unaffected visuomotor integration, individuals with PCS may be able to participate in this, and other sports, to assist the rehabilitative process. Far more research is required in this field to formally conclude as such, but the logical next step would be to assess visuomotor integration in more sport-specific paradigms for this rehabilitative trajectory.

7. Conclusions

This thesis assessed three populations on a perception-action integration paradigm. Athletes were not found to demonstrate kinematic differences related to their training when compared to non-athletes on this task. However, gaze strategies were found to differ between athletes and non-athletes in this study. These findings suggest that although navigation strategies did not differ between these groups, visual search strategies, and visual-attentional demands of this task, did. Such findings add to the understanding that sport-specific training influences perception-action integration, through our understanding of how athletes obtain visual information when determining navigation strategies. Further research is required to assess sport-specific navigational strategies through a more context-specific paradigm.

This thesis did not identify visuomotor deficits in athletes with PCS through the current paradigm. These findings suggest that these individuals have likely adapted to their injury and demonstrate equal ability in gaze and navigation strategies to specifically-trained athletes on this task. As such, further research is required to assess the cognitive, motor, and sensory-motor deficits that persist with the persisting physical symptoms of PCS as individuals with PCS do not demonstrate similar visuomotor deficits to individuals with acute concussions, likely illuminating differences between these injuries.

Appendix A: Inclusion & Exclusion Criteria

Non-Athlete Group

Inclusion	Exclusion
• Female • Age 18-25 years • Ability to walk 10m unassisted • Normal or corrected to normal vision	• Dance experience (any level) • Sport Participation above house league level • Neurological impairment including: Recent history of concussion, MS, etc… • Lower body injury

Athlete Group

Inclusion	Exclusion
• Female • Age 18-25 years • Ability to walk 10m unassisted • Normal or corrected to normal vision • >250 hours sport participation in previous 2 years	• Dance experience (any level) • Neurological impairment (for example: recent history of concussion, muscular sclerosis) • Lower-body injury

PCS Group

Inclusion	Exclusion
• Female • Age 18-25 years • Ability to walk 10m unassisted • Normal or corrected to normal vision • History of concussion > 2 months prior to experimental participation • Diagnosis of PCS by a healthcare practitioner • Participation in competitive sport prior to sustaining concussion (varsity level or higher).	• Dance experience (any level) • Neurological impairment other than concussion (for example muscular sclerosis, stroke) • Lower-body injury • Any contraindications to walking in a room lit by fluorescent lights for approximately 45 minutes (i.e. light sensitivity)

Appendix B: Informed Consent Form

Informed Consent Statement
Wilfrid Laurier University

How we use Vision to Guide our Obstacle Avoidance Strategies

You have been invited to participate in a research study. The purpose of this study is to determine how different populations use visual information to guide their actions when navigating through a cluttered environment. The study will be conducted by primary investigator, Carmen Baker and supervised by Dr. Michael Cinelli from the Department of Kinesiology and Physical Activity at Wilfrid Laurier University.

Carmen Baker
66 Hickory street
Northdale Campus Rm. N104/107
Waterloo, ON
N2L 3C5

Dr. Michael Cinelli, Ph.D.
75 University Ave. W
Bricker Academics Rm. 511
Waterloo, ON
N2L 3C5

Information

Part 1: The experiment is designed using a 10-metre pathway with two obstacles placed at 5m down the path on either side of the midline of the room. The two obstacles will create a horizontal aperture varying between 0.9-1.7 the participants' shoulder widths. The participants will be asked to walk naturally toward the goal placed along the midline at the end of the travel path, but asked to stop walking after 1m. At this point they will be asked a perceptual judgement question, "continuing at your current pace, do you believe you could fit through the aperture?"

The experiment has been designed to include a mandatory 5-10 minute break while the second half of the experiment is setup.

In the second part of the study, the two obstacles will be placed 3m, 5m, or 7m down the path on either side of the midline of the room. The two obstacles will create an aperture and the distance between the two obstacles will vary between 0.9-1.7x the participants' shoulder widths. The participants will be asked to walk naturally towards the goal placed along the midline at the end of the travel path. No direct instructions will be given with regards to having to walk between or around the obstacles. The path will be clear of any other obstacles and open space will be present on the outer side of each obstacle. The aperture widths will be randomized and the entire study should take approximately 1 hour to complete.

The study will measure body kinematics to determine how individuals walk to the goal. Kinematic data will be collected using an NDI Optotrak motion tracking system. Five light-emitting markers will be attached to the skin of the participants by using double-sided 3M tape (if individuals are allergic to tape a fitted t-shirt can be worn to prevent tape adhering directly to the skin). The markers emit low voltage light many times per second so that the camera system is able to capture the 3-dimensional coordinates of each marker. Any excess wires will be taped to clothing using transpore tape to avoid possible injury. Additionally, gaze tracking data will be recorded by the ASL Mobile Eye system. Participants will wear a set of glasses equipped with two cameras: one records movements of the eye, where the other records the visual scene. Please note that none of the above video tracking data has the ability to identify individuals through recordings (no images will be taken of participants' faces or anything that may reduce their anonymity).

Risks

Throughout the study, participants may experience fatigue or feel unbalanced while standing or walking. A previous concussion may increase the chance of tripping or colliding with obstacles. Participants may experience a loss of self-confidence if they are unable to perform the task properly. Participants are asked not to worry and to perform the best they can. Participants can take a break at any point during the procedure.

A risk of falling or colliding with obstacles is present due to the nature of the task. Spotters will be present to provide assistance to the participants throughout the experiment. Participants will have a scheduled break half way through the study and can request to sit at any point of the study. Participants may experience skin irritation from the markers if they are allergic to adhesive, however they have the option of performing the experiment in tight clothing that the markers may be adhered to in this instance.

Previously concussed individuals: Participating in this study may result in the recurrence of physical symptoms of concussion. As such, the re-emergence of any physical symptoms of concussion will lead to the immediate termination of your participation in this study. However, participation in this study is no greater risk to aggravating concussive symptoms than every-day life (including walking around campus).
I have read and understand these risks. Initials ____________.

Inability to participate in the study for any of the above reasons or for any recurring concussive symptoms will be assessed and monitored by the participant. They may choose to discontinue the study at any time without penalty for these or any other reason.

If an individual feels they are unable to continue the study, participants are able to withdraw at any time.

Benefits

Participants will be rewarded with a $8 gift card to Tim Horton's restaurants.

Although participants may become tired during the testing or feel unstable, participation in this study will greatly help in the understanding of the relationship between walking in cluttered environments (choosing paths to take around objects) and cognitive state. The results from the study will also aid in furthering the understanding of effects of athletic involvement and concussion on aperture crossing and walking through cluttered environments. The participants will also gain the knowledge and experience of how gait (walking) research is conducted.

Confidentiality

Participants will be assigned both a code name and an identification number. Only the investigators will know the association with personal data. Experimental data will be stored separately from personal data and all information.

During the report of results, participants will be identified using their assigned numbers and participants will never be identified in presentations or reports of the research. All data will be kept for 7 years in the LPMB research lab and kept in a locked cabinet.

Publication

The information and data collected from this study will be used for publications and upcoming conferences.

Feedback

After the participant has completed the experiment they will be told the purpose of the study, what we expect to find and what previous research has been found. If the participants are interested, they could have a copy of Carmen Baker's final KP490 Abstract of findings.

Contact

If you have questions at any time about the study or its procedures (or you experience adverse effects as a result of participating) you may contact the researcher, Dr. Michael Cinelli at (519) 884-0710 x 4217 or Carmen Baker at (519) 884-0710 x 4775. The project has been reviewed and approved by the University Research Ethics Board at Wilfrid Laurier University. If you feel you have not been treated accordingly to the description 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 13) 4994 or rbasso@wlu.ca.

Participation

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study your data will be returned to you or destroyed. You have the right to omit any questions/procedures 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 _____________________________ Date ____________

Date of last concussion (as determined by an athletic therapist or doctor): _________________________

Date of most recent symptoms of concussion (headache, nausea, dizziness): _______________________

Do you play a sport? ☐
At what level? _______________________
Which sport?_________________________

Please provide an email address if you wish you receive a summary of the findings of this study

Email address:______________________________

Appendix C: Health History Questionnaire

Health History Questionnaire

Participant ID:_________________________ M/F

1. At what age did you begin playing organized sport?____________________
2. How many years have you played? _____
3. Do you wear a mouth guard while playing? __yes __no

If yes, what kind?
___stock ___boil & bite
___custom, front teeth ___custom, all

4. Have you ever suffered from neck pain within the past 6 months? __yes __no

5. Have you ever suffered a concussion? __yes __no __not sure

6. If yes to #5,
a) How many times while playing sport in the past year? _____

b) Date of last concussion?___________

c) How long did the symptoms last (for last concussion)?
__ 1-3 days __4-7 days __8-10 days __ 11-14 days ___2-3 weeks ___ < 1 month
__<2 months __<3months ___<4 months
__<5 months __<6months ___>6 months

d) Who told you that you could not play because of the last concussion?(select all that apply)
__myself __coach __team therapist
__family doctor __chiropractor __other

e) After the last concussion, how long did you refrain from physical activity?
__ 4-7 days __8-10 days __11-14 days
__15-21 days __more than 3 weeks

7. Have you ever been knocked unconscious? __yes __no

8. If yes to #7,
a) How many times in the past 6 months? _____
b) What is the longest duration you've been knocked unconscious? _________

9. In the past 6 months, after being hit in the head in sports, have you experienced any of the following symptoms:
__ confusion __ getting "dinged"
__ headaches __ balance problem
__ nausea __ getting "bell rung" __ dizziness
__ ringing in the ears __ blurry vision
__ poor memory
other:___________________

10. 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/ 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
Feeling slowed down	0	1	2	3	4	5	6
"don't feel right"	0	1	2	3	4	5	6
Hard to concentrate	0	1	2	3	4	5	6
Feel in a "fog"	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue/ 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	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/ anxious	0	1	2	3	4	5	6

Appendix D: Risk Taking Questionnaire

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 α = .78), and those associated with the risk-perception scores, from .70 to .81 (mean α = .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 Moderately Somewhat Not Sure Somewhat Moderately
Extremely

Unlikely Unlikely Unlikely Likely Likely
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.

Appendix E: Study 1 - Additional Analyses

ML COM at the time of Passing – Directional Values

It was important to identify and report variability in decision making. As such, direction of deviation was assessed through entering ML COM values into mixed-model ANOVA (group by gap size by obstacle distance). Post hoc analyses were conducted using Bonferroni comparisons. It must be understood that high variability may lead to very low average ML COM values as participants who deviated once to the right (positive values) would cancel out deviations to the left (negative values).

A main effect of gap size was observed ($F_{(1.67, 88)}$=5.79, p<.01, β =.56). Post hoc analyses revealed participants deviated around obstacles that created gaps equal to 0.9 and 1.1 x SW ($\bar{x}$=29.23, 14.55 respectively), and walked between obstacles that created gaps of 1.3 x SW or greater ($\bar{x}$=.95, -1.07, .80 respectively, p<.01). A trend of obstacle distance was observed ($F_{(2, 44)}$=3.83, p=.03, β =.41), suggesting that participants tended to deviate more consistently wider around, or more consistently to the right of, obstacles located at 7m ($\bar{x}$=10.50cm) compared to those at 3m ($\bar{x}$=6.24cm). A trend was observed identifying a weak interaction between obstacle distance and group ($F_{(1.88, 44)}$=4.39, p=.02, β =.46), where athletes tended to deviate wider around, or to the right more frequently, than non-athletes when obstacles were located 3m from the start ($\bar{x}$=15.9, -3.44 respectively). No effect of group was identified ($F_{(1,22)}$=3.07, p=.09), nor were interactions between distance and gap, or group and gap were observed.

Unique ANOVAs were conducted for each obstacle distance. No effect of gap size was identified when obstacles were located 3m from the start (p=.05, β =.33). An effect of group was also not identified (p=.02, β =.42). This potential trend resulted from athletes tending to circumvent to the right ($\bar{x}$=15.9±27.3) more consistently than non-athletes ($\bar{x}$= -3.83±30.0). An effect of gap size was identified when obstacles were located 5m from the start ($F_{(1.8, 88)}$=4.39, p<.01, β =.58), indicating that participants deviated around obstacles that created gaps of 0.9 and 1.1 x SW, but no effect of group was identified (p=.18, β =.1). A main effect of gap size was identified when obstacles were located 7m from the start ($F_{(1.75, 88)}$=6.15, p<.01, β =.61), identifying deviations around obstacles that created gaps of 0.9 and 1.1xSW. No group differences were identified (p=.2, β =.08).

Decision Making Variability

ML COM position at the time of passing - variability

A main effect of gap size was found ($F_{(3.19, 80)}$=4.53, p<.01, β =.70). Post hoc analyses revealed ML COM variability was significantly greater when obstacles created gaps of 1.1 x SW ($\bar{x}$=13.30) compared to those of 1.5 and 1.7 x SW ($\bar{x}$=3.42, 2.24 respectively, p<.01). No main effect of group was identified, nor were any interactions.

Discussion Points

When investigating ML COM position at individual obstacle distances, it must be noted that trends were identified when direction of deviation was examined, but that these effects were nullified when absolute value of ML COM position was assessed. Interestingly, a similar trend was observed for obstacle distance, indicating participants chose to deviate to the right more frequently when obstacles were located 7m from the start, compared to 3m (Figure 1). This directional trend is interesting as both sides of the room afforded similar action strategies (the obstacles were located equidistant from the midline of the room). As these trends were nullified when direction of deviation was eliminated, both groups appear to have similar navigational choices to deviate around and walk through similar gap sizes. Therefore, the minimal trend seen in direction of deviation at 3m may be a result of the dynamic stability that this short distance affords. Foot used for first step and/ or the planting foot for use in a step-wide strategy may have influenced this discrepancy (see Hackney & Cinelii, 2013). Yet, the statistical power of these effects were small-to-medium at best (β=.46, .41). Therefore strong conclusions on variability in direction of deviation cannot be drawn on group and directional differences without further assessment.

AP Safety Margin – Variability

AP safety margin variability (standard deviation) was assessed to better understand trends of group and condition differences and interactions. An interaction between obstacle distance and gap size was found to be nearing significance ($F_{(1.96,6)}$=3.77, p=.09, β =.46). It appears that participants are vastly less consistent in maintaining an AP safety margin when approaching obstacles that create gaps of 1.1 x SW compared to 0.9 x SW at 3m ($\bar{x}_{0.9}$=14.92cm versus $\bar{x}_{1.1}$=27.54cm). Where AP safety margin variability is much greater at 3m, it tended to decrease when participants interacted with obstacles that created gaps of 1.1 x SW at 5m and 7m ($\bar{x}_{0.9}$=18.40, 13.91 $\bar{x}_{1.1}$=7.09, 11.53cm respectively).

Appendix F: Analysis of Error Trials

Error responses were recorded for each participant (see Table). Four athletes were found to make errors, three of whom only made a single error (total five errors with no obstacle contacts); eight non-athletes made errors (five individuals made two errors, three individuals made a single error for a total of 13 errors with 3 obstacle contacts); and six athletes with PCS were found to make errors (two individuals made one error, one made two errors, and three others made three errors for a total of 13 errors with no obstacle contacts). Although it was possible for participants to gain tactile or other feedback on certain trials from contacting the obstacles, which may influence their subsequent navigation strategies, the effect of an obstacle contact was verbally downplayed ("not a big deal"). Further, of all of the navigational errors, a very small proportion of them were obstacle contacts (most resulted from shoulder rotations or shrugs), suggesting that in a large majority of the errors observed, perception-action integration strategies were not affected by tactile feedback. As participants were not informed of the size of the gap that they erred in attempting to pass, this likely also negated any carry-over from interacting with the condition more than the typical two times.

Group	Number of participants who made an error	Maximum individual number of errors	Total Errors	Total obstacle contacts
Non-Athletes	8	2	13	3
Athletes	4	2	5	0
Athletes with PCS	6	3	13	0

Appendix G: Risk Taking Score Analysis

Risk taking was assessed using the 30 item DOSPERT Scale (Blais & Weber, 2006). This scale assesses risk in five domains of life, including recreational risk, ethical risk, financial risk, healthy/ safety risk, and social risk (see Appendix D). All items were assessed on a seven-point likert scale, with individuals rating how likely they would be to engage in each item (extremely unlikely to extremely likely). Overall risk score was assessed out of 210 (30 items x Maximum score of 7). Recreational risk was also assessed; scores were calculated out of 35 (5 items x Maximum of 7). Athletes with PCS were requested to complete the questionnaire as they would if they were not injured (i.e. one participant voiced that she would have enjoyed completing many of the activities, but would not participate in any currently, as they would exacerbate her symptoms).

Total risk and recreational risk taking scores were correlated with anterior-posterior (AP) and medial-lateral (ML) safety margins. These analyses were conducted for all groups. Groups were collapsed to identify whether risk was a better identifier of safety margin, as opposed to the *a priori* designation of group (athletes, non-athletes, and athletes with PCS). Neither total risk score nor recreational risk score were found to correlate with AP safety margin, nor ML safety margin.

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