Aperture Crossing in Challenging Environments: An Examination of the Factors that Influence the Passability of Narrow Spaces

by

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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

- Amy Hackney

STATEMENT OF CONTRIBUTIONS

Versions of the experiments presented in this dissertation have been published. I, Amy Hackney, was the main contributor and lead author of the work that has been published and the manuscripts in preparation for publication. My contributions included the majority of research design and data collection, all of the data processing, data analysis and interpretation of the results as well as the writing of this thesis.

Chapter Two and Chapter Four are versions of two published journal articles entitled "Is the *critical point* of aperture crossing scaled to the person-plus-object system?" and "Does the passability of apertures change when walking through human versus pole obstacles?" respectively. Dr. James Frank and Dr. Michael Cinelli are co-authors on both of these manuscripts. Their contributions to this publication included support with the design of the experiment and editorial assistance of the manuscript. Chapter Three is also a version of a published manuscript entitled, "The effects of elevated and narrow path walking on aperture crossing". Dr. James Frank and Dr. Michael Cinelli again acted as co-authors for similar reasons as outlined for the above-mentioned chapters. Luke Denomme is listed as a secondary author for his assistances with research design and the data collection process.

ABSTRACT

In order to get to where we need to go, locomotion often involves walking through narrow spaces. Whether an aperture affords passage is thought to be determined by the body size/aperture size relationship. For normal, ground-level aperture crossing, spaces 1.3x the shoulder width or smaller are considered impassible (requiring a shoulder rotation) and as such, 1.3x SW is said to be the *critical point* of aperture crossing. However, daily activities often involve navigating through apertures under more challenging circumstances, such as when walking through a busy airport while carrying luggage. As such, additional factors other than simply the body size and the aperture size may contribute to whether an aperture is deemed passable. Therefore, the purpose of this thesis was to investigate how the factors associated with challenging environments contribute to the way in which the body-environment relationship determines the affordance of aperture crossing.

Through a series of experiments, participants walked through apertures: 1) while carrying a wide object, 2) under conditions of increased postural threat, 3) where the narrow spaces were created by other individuals, and 4) where there were multiple, misaligned apertures. In general, aperture crossing behaviour was monitored through the *frequency* and *magnitude of shoulder rotations* at time-of-crossing (TOC), the *critical point,* the amount of space between the shoulders and the obstacles at TOC (*spatial margin*), the position of the body relative to midline *(M-L COM at TOC)* and the walking speed leading up to and crossing through the aperture (*approach velocity* and *velocity at TOC*).

The results from study one reveal that the passability of apertures adapts to objects being carried by rescaling the body-environment relationship to consider the new person-plus-object width and maintaining a *critical point* of 1.3x the widest dimension. However, this rescaling occurred at different rates across individuals. Studies two and three demonstrate that action capabilities (postural threat) and characteristics of the aperture (people instead of poles) alter the passability of apertures, as evident by more cautious crossing behaviours. Specifically, individuals maintained a larger *critical point,* a higher *frequency* and larger *magnitude of rotation,* as well as a slower *approach velocity* and *velocity at TOC*. Lastly in study four, rather than walk through the center of an aperture and equalize the size of the *spatial margin* of each shoulder (as observed in single aperture crossing), individuals walking through multiple misaligned apertures reduce the size of the *spatial margin* by walking closer to the object nearest midline. Furthermore, participants choose to rotate their shoulders at apertures that would not normally require a rotation, likely in an attempt to maintain the straightest possible walking path.

Together, these studies suggest that additional factors other than the body size/aperture size ratio are considered when determining the affordance of aperture crossing. Specifically, in addition to supporting the idea that individual abilities are an important contributing factor to the identification of affordances, these results demonstrate that the affordance of aperture crossing is influenced by: 1) the level of postural threat, 2) characteristics of the aperture, and 3) the number and position of apertures. Understanding the typical behaviour for walking through narrow spaces and knowing what and how specific factors influence the passability of apertures provides the necessary groundwork for understanding how these behaviours are altered with age or disease and can provide insightful suggestions for the future design of cluttered environments.

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First and foremost, I would like to express my most sincere gratitude to my supervisor Dr. James Frank. Your wisdom, insight and passion for research has been essential to the completion of this thesis. I would also like to acknowledge Dr. Michael Cinelli. Thank you for getting me excited about research during my undergraduate degree, for your continuous support throughout all of my training and for treating me like family. Jim and Mike, you are both truly inspiring people.

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DEDICATION

To my parents.

Thank you for supporting my decision to pursue a PhD and for providing constant support and encouragement along the way. I would never have made it here without you.

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SUPLLEMENTARY MATERIAL

LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
A-P	Anterior-posterior
A/O	Aperture width / Object width
A/S	Aperture width/ Shoulder width
BOS	Base of support
cm	Centimeters
COM	Center of mass
CNS	Central Nervous System
CP	Critical point
Deg / ^{o}	Degrees
DOSPERT	Domain specific risk-taking questionnaire
GLM	General linear model
H	Height
HMD	Head-mounted display
Hz	Hertz
in	Inches
IREDs	Infrared-light emitting diodes
L	Long
m	Meters
m/s	Meters per second
M-L	Medial-lateral
MPD	Minimum predicted distance

OA	Older adults
s	Seconds
SD	Standard deviation
SE	Standard error
SW	Shoulder width
TOC	Time of crossing
TTC	Time to contact
T10	Tenth thoracic vertebrae
VR	Virtual reality
W	Width
YA	Young adults

DESCRIPTION OF DEPENDENT VARIABLES

Approach phase	Begins after the third step is taken at the start of a trial and continues until the anterior-posterior (A-P) center of mass (COM) is 1.5m from the aperture.
Approach velocity	Change in displacement of the A-P COM over time; averaged over the approach phase.
Critical point	The largest aperture width that divides passable and impassable apertures: where there is a shift from shoulder rotations to no rotations at the time of crossing (TOC); individual critical points were determined by finding the largest aperture width where the participant rotated his/her shoulders on 60% of the trials; the average critical point for a group of participants represents the aperture width where the rotation magnitude is statistically different than the average rotation for straight walking.
Distance from center	Location of the medial-lateral (M-L) COM) relative to the center of the aperture when the A-P COM crossing through the aperture.
M-L position at TOC	Absolute position of the M-L COM when the A-P COM crossing through the aperture.

Onset of rotation	Distance of the A-P COM relative to the obstacles when the shoulder rotation magnitude falls outside two standard deviations of the average rotation during the approach.
Rotation magnitude	Angle between the infrared light-emitting diodes (IRED) markers on the left and right shoulders at the TOC; for the purpose of determining the frequency of rotation, a significant rotation occurred if the magnitude of rotation fell outside two standard deviations of the average rotation during the approach.
Spatial margin	Absolute distance between the inner edge of the obstacle and the IRED marker of the shoulder closest to midline at the TOC.
Trunk roll	Absolute angle between the IRED marker located on the tenth thoracic vertebrae (T10) and a calculated imaginary point between the shoulders and then averaged over the approach phase.
Velocity at TOC	Instantaneous velocity when the A-P COM passes through the aperture.

A visual representation of these dependent variables are presented in Appendix A

- Chapter 1 -

GENERAL INTRODUCTION

1.1 The Problem

The sole purpose of human gait is to transport the body safely and efficiently across the ground and toward an end-goal (Winter, 1991). Although locomotion may seem as though it is an elementary task, the demands placed on the central nervous system (CNS) when walking through cluttered environments are anything but simple. Navigating through the world involves placing the foot onto isolated foot holds, stepping over or onto objects, circumventing obstacles and passing through narrow spaces. As such, successful navigation requires the ability to appropriately adapt the orientation and the movements of the body to clear obstacles and maintain stability under a variety of environmental demands. The problem associated with the organization of such behaviour was articulated by Warren (2006):

> The ability to produce stable and adaptive behaviour raises two constituent issues. On one hand, it implicates the coordination of action, such that the many neuromuscloskeletal components of the body become temporarily organized into an ordered pattern of movement. On the other hand, it implicates perception, such that information about the world and the body enables appropriate actions to be selected and adapted to environmental conditions. (p. 358).

How humans organize behaviour and generate movement patterns to successfully navigate through cluttered environments and avoid obstacles has long been an area of interest in disciplines such as motor control, psychology, biomechanics, and neuroscience. The majority of this research has attempted to characterize how the CNS controls movements that are strongly coordinated with the environment. Aperture crossing protocols in particular, offer an excellent means of studying the relationship between the body and the environment because of the direct link between perception and action. To date, research has observed that the manner in which individuals control their actions under normal walking conditions is quite robust. Individuals pass unaffected through apertures larger than 1.3x their shoulder width (SW), but require a modification to their body orientation, such as a shoulder rotation, for spaces smaller than this value (Warren & Whang, 1987). The division between passable (no rotation necessary) and impassable spaces (rotations required) are consistent across individuals of varying body sizes (Geuss, Stefanucci, Creem-Regehr & Thompson, 2010; Lepecq, Bringoux, Pergandi, Coyle & Mestre, 2009; Hackney, Vallis & Cinelli, 2013; Wilmut & Barnett, 2010). Although a review of the literature (Section 1.3.2) reveals that walking through a single, stationary aperture in normal, flat-ground environments is well understood, numerous avenues remain unexplored despite the fact that understanding how individuals behave in such situations will provide promising future directions for aperture crossing research. Gaining an appreciation of whether aperture crossing behaviours are altered under the various challenges faced on a daily basis provide a more comprehensive understanding of how the perception-action system controls movements and establish the groundwork necessary for future studies examining aperture crossing with special populations.

In addition to contributing to the perception-action literature, understanding how challenging environments alter the passability of narrow spaces may also provide useful information for the architectural design of spaces concerned with human traffic flow. A new affordance-based approach to architectural design has emerged in recent years from the perception-action literature, in an attempt to bring functional factors into consideration. Current standards of how spaces and objects should be built are based on anthropometric standards or personal judgement (Normal, 1999; Panero & Zelnick, 1979). However, this purely anatomical approach disregards the functional interactions users have with the world and can be problematic when one considers the diverse abilities present across both a young and older population. For example, as outlined by Warren (1995), the functional boundary between a stair that is and is not climbable for an older adult (OA) may be different than the geometric one simply because of limitations in flexibility and strength. As a result, Warren (1995) put forth a recommendation to increase the original anthropometric standard for passage widths from 21in (53cm) to 25in (64cm) in order to accommodate the functional boundary associated with walking through apertures in a larger portion of the population. Establishing how this functional boundary changes in challenging aperture crossing environments may provide more detailed recommendations when designing spaces for specific uses.

In order to expand on the current understanding of how individuals control their actions when successfully walking through small spaces, aperture crossing paradigms were used throughout this thesis with the specific aim of determining how crossing behaviour is influenced by challenging environmental conditions. The remainder of this chapter will provide readers with an understanding of how locomotion is guided to an end-goal while avoiding collisions with obstacles through a discussion of the visual control of locomotion, perception and action coupling, and a review of the current aperture crossing literature. Each of the subsequent experimental chapters (Chapters 2 through 5) will review the relevant literature and hypotheses necessary for establishing the foundation for the specific research questions being addressed within each chapter.

1.2 Visual Control of Locomotion

Although successful human locomotion requires the integration of visual, vestibular, and kinesthetic inputs, visual information is particularly significant for adapting behaviours when walking in cluttered environments. The visual system provides three important types of information to the observer; 1) information about the layout of surfaces and relative position of objects at a distance, 2) the relative position of body segments to one another, and 3) information about the relative position of body segments to objects in the environment (Patla, 2007). Individuals therefore use visual information to control their actions in a proactive, feed-forward manner whereby the observer can identify what actions are necessary and whether modifications are required without having to rely purely on reactive control. With this information, vision can then play five major roles during adaptive locomotion, including the detection of hazards, deciding on an appropriate avoidance maneuver, preparing and initiating the chosen maneuver, and making any necessary adjustments (Tresilian, 2012).

How vision is used during locomotion is well documented in the literature. During unobstructed locomotion for example, people look in the direction in which they are travelling and roughly two steps ahead of the current location (Grasso, Prevost, Ivanenko & Berthoz, 1998; Hollands, Vickers & Patla, 2002; Vickers & Patla, 1997). When obstacles clutter the travel path, this fixation is directed at the upcoming object to determine in advance what locomotor adjustments may be required (Patla, Prentice, Robinson & Neufeld, 1991). Furthermore, although intermittent visual sampling is sufficient to guide unobstructed locomotion, the frequency of visual sampling must increase when obstacles are present in order for the object to be cleared successfully (Patla, Adkin, Martin, Holden & Prentice, 1996). This is particularly important when accurate foot placement is necessary for success. Lee and colleagues (1982) demonstrated that vision drives the final four foot placements of a long jumper in order to ensure he or she accurately steps on the take-off board. A similar dependence on vision has been observed for aperture crossing. When walking towards and passing through a set of moving doors, vision guides the final locomotor adjustments and determines the changes in velocity that are necessary (if any) to pass through safely (Cinelli, Patla & Allard, 2009; Montagne, Buekers, Camachon, De Rugy & Laurent, 2003). Additionally, when individuals complete a similar task but with a novel mode of transportation, such as when using a wheelchair, fixations directed at the aperture occur more frequently and for longer periods of time (Higuchi, Cinelli & Patla, 2009). This change in gaze behaviour likely reflects the need to gather more information about the environment before making any alterations to actions. The abovementioned studies provide evidence for the role of vision in the coordination of movement and highlights its importance for successful locomotion in cluttered environments.

The fact that human locomotion relies so heavily on visual information implicates the role of perception in the generation and coordination of adaptive behaviour. Exactly how perception is linked to action is a topic of much debate, as two contrasting theories currently exist in the literature: indirect and direct perception. Proponents of indirect perception describe the act of perceiving as the construction of mental representations of objects. In this perspective, sensory input does not provide enough information about objects and events to be rendered meaningful and useful to the action system (Michaels & Carello, 1981). Instead, the formation of rich and accurate perceptions are thought to involve a complex set of elaborations to make the sensory input useable. The theory of indirect perception assumes that the CNS provides these additions to its stimulation by adding together stored mental representations associated with the sensory stimulus (Rock, 1997). On the contrary, the assumptions that outline the theory of direct perception are very different from that of indirect perception. Supporters of direct perception describe the act of perception as the direct acquisition of information from the environment (Galotti, 2013) and that the basis of perceptual richness is not in the elaborate cognitive processes applied to the sensory input, but in the richness of the stimulation itself (Michaels & Carello, 1981). The stimulus is believed to provide sufficient information to the perceiver without the need for elaboration. Two major components of the theory of direct perception are optic flow and the concept of affordances, both of which will be discussed in more detail in the section that follows (Section 1.3).

The direct and indirect debate has not been resolved, as there are strong arguments and convincing evidence to support both theories. Perhaps the question should not be focused on whether the theories are mutually exclusive, but rather which theory best explains perception within a given scenario. As suggested by Galotti (2013), indirect perception may be prominent in situations that are variable, unpredictable and where the rules are abstract, such as when interpreting a dancer’s movements. Meanwhile, direct perception may guide actions that occur within a predictable environment, where there is a direct link between perception and action, such as locomotion. Therefore, for the purpose of generating the research questions and hypotheses within this thesis, the theoretical framework associated with direct perception, specifically the concept of affordances (described in Section 1.3) will be used.

1.3 Perception and Action

“In order to move throughout the world, one must be able to perceive it” (Gibson, 1979). Perception and action are coupled, such that visual perception guides the action required to navigate safely through an environment and in turn, the execution of that action will update perception. Gibson (1979) argued that light hitting the retina contains highly organized information that requires very little interpretation from higher order processes. Certain aspects of the visual stimuli remain invariant despite changes over time or changes in our relationship to them. It is these invariances that help guide the perception-action relationship. Johansson (1973) demonstrated the idea of visual invariance by showing that participants can immediately recognize an activity being completed by a model despite only receiving visual information from lightbulbs attached to the joints of the body. Similar results have been observed for identifying a male versus a female model in motion by simply viewing the lightbulbs moving (Kozlowski & Cutting, 1977). In both studies, the motion of the lights relative to one another provided enough information to perceive the action being performed.

Gibson (1979) coined the term optic flow to describe the pattern of apparent motion of objects, surfaces and edges in a visual scene caused by the relative motion of the observer and his or her environment. Changes in the flow of the optic array contains important information about the type of movement that is taking place. Specifically, it is thought that individuals can derive essential pieces of information about locomotion from the characteristics of this array (Gibson, 1979). For example, flow of the array indicates movement while non-flow suggests the observer is stationary. Furthermore, outflow specifies that the individual is approaching the object while inflow identifies retreating from it. Additionally, the focus of this outflow indicates the direction of locomotion, and the shift of the center of the outflow reveals that this direction has changed.

An excellent example of the use of optic flow to control actions was first observed in pilots during World War II. Gibson (1958) suggested that pilots use information about the apparent movement of the ground, the clouds and objects relative to the plane in order to navigate the plane towards the runway. Warren and colleagues (2001) provided further evidence of the use of optic flow to control action by demonstrating its importance in the control of locomotion. In a virtual environment, participants walked toward an end-goal while the amount of optic flow available to them was manipulated. Although participants steered toward the target goal in all manipulation conditions, the trajectory of the walking path reflected the increasing reliance on optic flow (i.e., the path trajectory became more linear) as it was added to the visual display (Warren, Kay, Zosh, Duchon & Sahuc, 2001). A number of studies have confirmed that optic flow dominates steering control (Harris, & Carre, 2001; Turano, Yu, Hao & Hicks, 2005; Wood, Harvey, Young, Beedie & Wilson, 2000), modulates walking speed (Harris, Jenkin & Zikovitz, 2000; Pailhous, Ferrandez, Fluckiger & Baumberger, 1990; Prokop, Schubert, & Berger, 1997), and plays a central role in the adaptation of visuo-locomotor mapping (Bruggerman, Zosh & Warren, 2007).

An important aspect of perception-action coupling is that the visual information available to a perceiver exists within a body-environment ecosystem (Michaels & Carello, 1981). This body-environment interaction is thought to be responsible for determining what actions are available for a particular animal within a given environment (Figure 1.1). Gibson (1979) referred to this as the ability to perceive an affordance. By definition, an affordance is the fit between the size of the animal and the size of the environment that make a particular action possible (Franchak & Adolph, 2014a; Gibson, 1979). In its simplest sense however, an affordance can be considered as what the environment means to a perceiver with respect to the actions that can, or need to be performed. Undoubtedly, visual information such as optic flow plays a crucial role in identifying affordances.

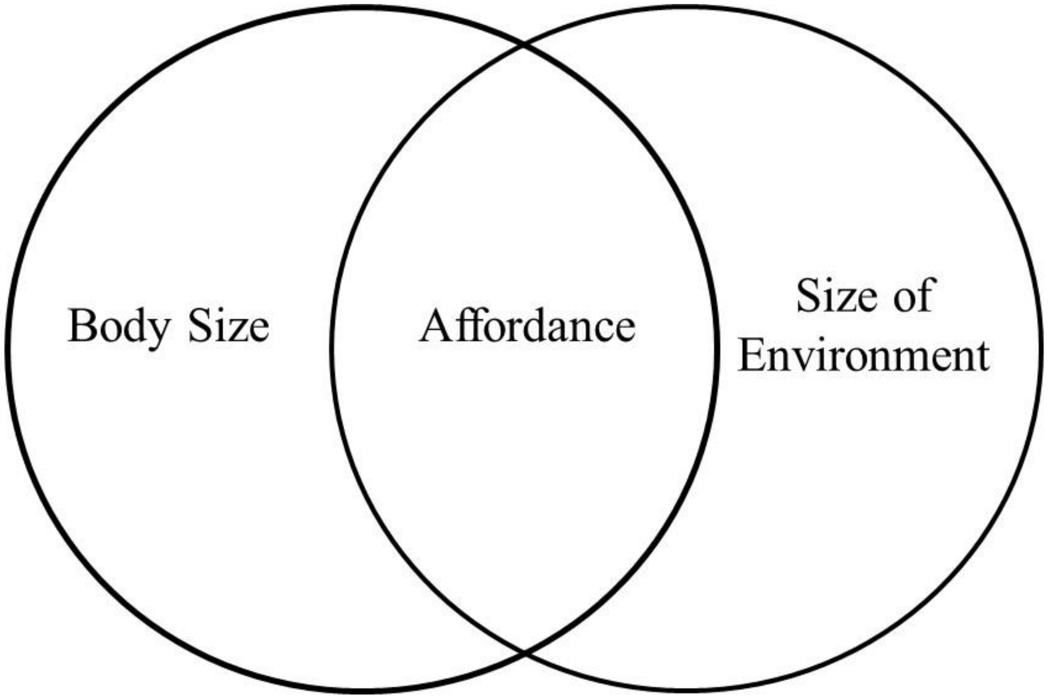

Figure 1.1 – Gibson (1979) argued that the affordance of an environment or an environmental object is determined by the fit between size of the environment and the size of the body.

A large body of literature exists to support the notion that affordances are determined by the fit between the environment and the action system. In animal research, it has been demonstrated that frogs detect if a narrow opening affords passage based on its own body size (Ingle & Cook, 1977), a praying mantis will decide if a particular prey affords being attacked depending on its own grasp size (Hollings, 1964) and clams will attack or retreat based on their size relative to the size of the prey (Branch, 1979). In humans, Warren (1984) demonstrated that the affordance of stair climbing is based on the length of the leg of the perceiver. Specifically, a stair is considered climbable if the ratio between riser height and leg length is less than 0.88x the leg length. Likewise, the affordance of aperture crossing is based on the size of the shoulders where apertures larger than 1.3x SW are considered passable (Warren & Whang, 1987). Similar body-scaled affordances in humans have been observed for actions other than locomotion. For example, the eye-height of a perceiver determines if a surface affords sitting (Mark, Balliett, Craver, Douglas & Fox, 1990) and the size of the hand will determine whether an object affords grasping (Hallford, 1983). Together, these studies not only demonstrate that the perception of affordances occurs in a body-scaled fashion, but that the part of the body that is used to identify an affordance differs based on the task about to be performed.

As noted by Gibson (1979), the visually specified environment offers indefinite possibilities for action. An environment or an environmental object can be classified as being climb-able, sit-table, pass-able, etc. As evident from the above-mentioned experiments, the body is most often used to scale the environment to these action-specifying units. However, no single body part can be used to specify all actions. For example, the width of the shoulders is sufficient for determining whether a narrow gap can be crossed, but it would be insufficient for specifying if an object can be grasped. Proffitt and colleagues (2013) suggested that affordances are not only determined by the fit between the body and the environment, but also by the demand of the task (Figure 1.2). As such, the demand will determine the type of actor the individual is to become (i.e., a grasper, a walker, a thrower etc.) and the aspect of the body relevant for completing such a task. In turn, this body part will be used to specify the environment in the appropriate body-scaled units. As a result, different aspects of the body can be thought of as *perceptual rulers* defining the environment in relationship to the task's relevant ruler (Lessard, Linkenauger & Proffitt, 2009).

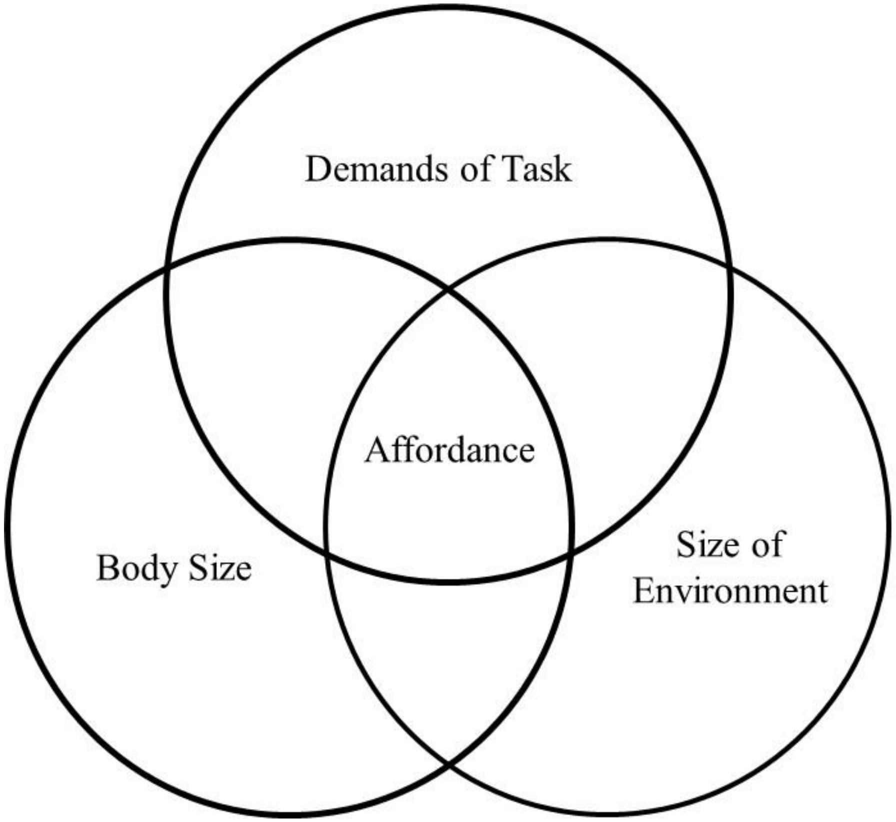

Figure 1.2 – As an extension of Gibson's (1979) concept of affordances, Proffitt (2013) suggested that affordances are determined based on the fit between the body, the environment and the demand of the task.

An individual's action capabilities and their subsequent behavioural repertoire plays a crucial role in defining the set of roles that a person can take within an environment. The ability to quickly and accurately scale the environment using the appropriate *perceptual ruler* is thought to be made possible through experience and learning (Proffitt & Linkenauger, 2013). In order to determine whether an action can be performed within a given environment, actors must scale the visual information to the relevant action boundaries, or in other words, to the limits of their behavioural repertoire. This requires that individuals learn the visual specification of their action boundaries for a great variety of actions (Proffitt, 2013). As stated by Gibson (1979), "infants practice looking at their hands for hours, for disturbances of optical structure that specify the niceties of prehension have to be distinguished". Similar extensive practice is observed for locomotion, where infants spend countless hours traversing their surroundings and falling down (Adolph, 2008). Perhaps the most prominent evidence of this need to explore the relationship between visual information and actions comes from the observation of infants as they transfer from sitting, to crawling and eventually to walking. A number of experiments have demonstrated that experienced crawlers will avoid crossing impossible cliffs, but novice walkers repeatedly attempt the gap (Adolph, 1997; Adolph & Tamis-LeMonda, Ishak, Karasik & Lobo, 2008; Kretch & Adolph, 2013). It is not until the child has learned how their movements are associated with optic flow and the visual information associated with their action boundaries are the *perceptual rulers* formed to specify the environment appropriately.

In addition to learning how visual information is related to actions, research has demonstrated that the *perceptual rulers* used to specify an environment in action-specific units are specific to the type and demand of the task at hand and are unaffected by the modulation of other *perceptual rulers*. Witt and colleagues (2004) used a treadmill adaptation task to recalibrate the *perceptual ruler* used to specify the extent of a walking path, which was thought to be specified in units associated with the energetic cost of traversing the distance (Stefanucci, Proffitt, Banton & Epstein, 2003). Upon completion of the treadmill adaptation task, participants made judgements about the length of the path with the assumption that they would either have to walk the distance blindfolded or throw a ball to the end of it. Those who intended to walk the distance judged the path as longer after the *perceptual ruler* had been recalibrated, while individuals who intended to throw the ball were unaffected by the manipulation (Witt et.al, 2004). The authors suggested that recalibrating walking effort likely had no effect on the action-specifying units necessary for throwing because the affordance would be specified in units related to throwing (i.e., the arm) and not in units related to walking.

If these so-called *perceptual rulers* are used to transform the environment into action-specifying units related to the individual, than one would expect that manipulation of these rulers to influence perception. A number of studies have demonstrated such effects on perceptual judgements (Bhalla & Proffitt, 1999; Canal-Bruland, Pijpers, & Oudejans, 2010; Linkenauger, Ramenzoni & Proffitt, 2010; Proffitt, 2008; Witt, Proffitt & Epstein, 2004). It is important to note that the majority of these studies test the effects of changing an individual’s potential for action on perceptual judgements, most commonly done by having participants make spatial judgements while remaining stationary. These studies only examine the perception side of the perception-action relationship and fail to actually measure the subsequent actions associated with these altered affordances. Since research has demonstrated that perceptual judgements about actual performance abilities that are made while stationary are not as accurate as those made during movement (Hackney & Cinelli, 2013a), it is important to establish an understanding of whether performance is also affected by changing one's potential for action.

Aperture crossing protocols in particular are an excellent way to examine the affordance of passageways, whether manipulations to the perception-action relationship (i.e., potentials for action) and the subsequent *perceptual ruler* used to specify the aperture influences the actions an individual will choose to pass through a narrow space. Studying the passability of apertures is particularly useful in understanding these relationships because: 1) they provide a testing environment where manipulation of the space between two obstacles can easily be controlled and examined, 2) they present a straightforward relationship between body dimensions and opening size thereby allowing affordances to be easily examined, and 3) they are an example of a task that humans encounter on a daily basis and should consequently, be well practiced. The following section provides a review of the current aperture crossing literature.

1.4 Aperture Crossing

The most common method of examining aperture crossing behaviours is to manipulate the width of a narrow opening and monitor both the timing and magnitude of action changes leading up to and crossing through the aperture. In laboratory settings, these narrow spaces are often formed from two panels that create a doorway or two pole obstacles placed on each side of the midline of the path, which together create a gap to pass through (Figure 1.3). In such scenarios, participants encounter a variety of aperture sizes that range from being much smaller than the width of the shoulders to up to two times its size. The variety of aperture sizes ensures that individuals are confronted with spaces that force a modification to their current body position while also encountering gaps that can be crossed without needing such a change.

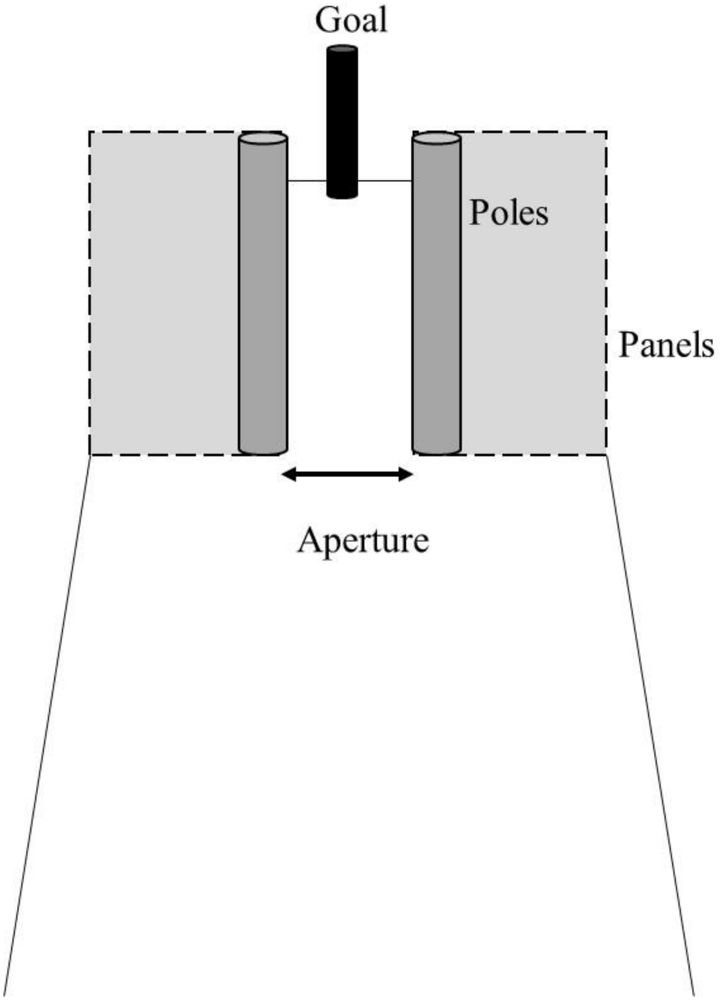

Figure 1.3 – A typical experimental setup for aperture crossing protocols. The width between the panels or poles vary from being very small (e.g., 0.8x SW) to very large (e.g., 2.0x SW).

Studies examining how individuals pass through these narrow openings report that the frequency and magnitude of shoulder rotations increase as the size of the space decreases (Hackney & Cinelli, 2011; Higuchi, Murai, Kijima, Seya, Wagman & Imanaka, 2011; Fath & Fajen, 2012; Keizer, De Bruijn & Smeets; 2013; Franchak, Celano & Adolph, 2012; Warren & Whang, 1987; Wilmut & Barnett, 2010). Furthermore, large-bodied individuals must rotate their shoulders more frequently and to a greater degree at larger gaps compared to those with smaller shoulder widths (Franchak, van der Zalm & Adolph, 2010; Stefanucci & Geuss, 2009; Warren & Whang, 1987). To account for the differences in body size, the width of the aperture is often scaled to the width of the shoulders (i.e., the largest horizontal width of the body). This creates a dimensionless *pi* value that represents the size of the space relative to the size of the individual (Gibson, 1979). When the size of this normalized aperture width reaches a point at which the individual must change from straight walking to producing a shoulder rotation at time-of-crossing (TOC), the *pi* value corresponding to this change in action is classified as the *critical point* (Warren & Whang, 1987). Although the literature often uses the terms *critical point* and action boundary interchangeably, for consistency purposes this thesis will refer only to the *critical point* to denote to the division between passable and impassable apertures.

Notably, Warren and Whang (1987) first observed that regardless of body size, the *critical point* for aperture crossing was 1.3x SW: participants produced a significant shoulder rotation for apertures that were 1.3x SW or smaller, but would walk straight through spaces larger than this ratio (Figure 1.4). Since the differences first observed between large- and small-shouldered individuals disappeared once the aperture width was normalized to body size, the authors concluded that aperture crossing must be a body-scaled task (Warren & Whang, 1987). A similar *critical point* was observed during unconfined aperture crossing tasks where participants were permitted to avoid passing through the opening all together if they felt inclined to do so. In this case the results were in line with the previous observations from Warren and Whang (1987), such that participants walked straight through apertures larger than 1.4x SW and needed to change their body orientation for apertures smaller than this ratio (Hackney et al., 2013). However, rather than rotating the shoulders, participants elected to deviate away from the straight walking path and avoid the aperture all together by walking around it. Together, these results demonstrated that a common *critical point* differentiates passable and impassable apertures and that the CNS considers the size of the shoulders when modifying actions to ensure safe passage through narrow spaces.

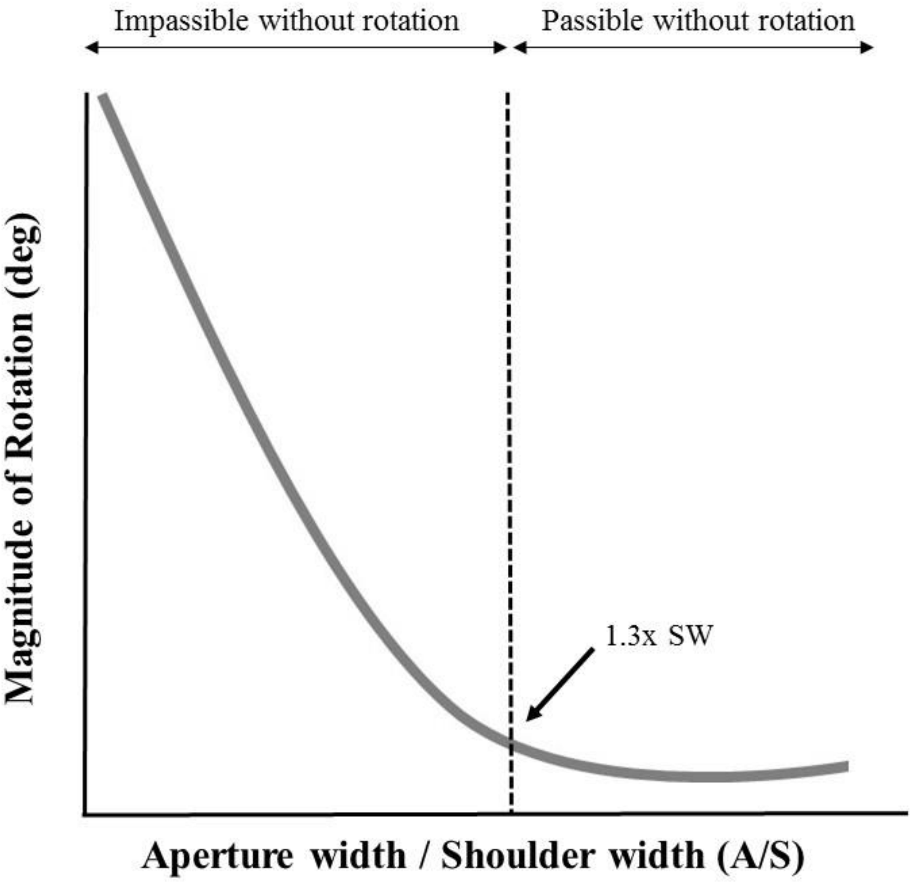

Figure 1.4 – Passable versus impassable apertures: when the width of an aperture is scaled to the size of the shoulders, spaces smaller than 1.3x SW require a shoulder rotation to pass through while apertures larger than this ratio do not.

Aside from shoulder rotations, research has also demonstrated that the initiation of a shoulder rotation and the initiation of changes in walking speed are also scaled to the size of the aperture, such that changes in these behaviours occur earlier for smaller versus larger openings (Wilmut & Barnett, 2010). Furthermore, it has been suggested that individuals aim to maintain a constant *spatial margin* (M-L distance between shoulders and obstacles at TOC). The degree of shoulder rotation at TOC for small apertures is controlled by the desire to ensure a *spatial margin* of 6-10cm (Higuchi, Seya & Imanaka, 2012). A *spatial margin* is also observed during unconfined aperture crossing when the opening is too small for straight passage. Individuals preserve an elliptical-shaped protective zone in the A-P and M-L directions by making earlier deviations from the straight walking path and moving farther in the M-L direction as the size of the aperture increases (Hackney et al., 2013). These results suggest that the CNS acts to maintain a buffer zone around the body large enough for any necessary gait adjustments to be made in the case of unexpected perturbations.

The fact that individuals preserve a safety zone around the body during aperture crossing is not surprising, as similar behaviours have been observed in obstacle circumvention tasks. Cinelli and Patla (2009) showed that when avoiding an approaching obstacle, individuals deviate off the straight path trajectory in order to maintain a similar distance between their body and the obstacle at the TOC. This behaviour occurs regardless of how fast the object is approaching the individual. Gerin-Lajoie and colleagues (2008) also demonstrated a desire to maintain a constant M-L clearance when circumventing a single object, even when the object’s movement characteristics were uncertain. From their work, the researchers determined that individuals maintain an elliptical-shaped protective zone around their body both in the A-P and M-L directions when circumventing obstacles. As with the aperture crossing literature, the researchers suggested that the role of this space was to provide a safety zone large enough to ensure sufficient time to perceive upcoming hazards and perform adjustments to gait in order to successfully avoid colliding with the obstacles (Gerin-Lajoie, Richards, Fung & McFadyen, 2008; Cinelli & Patla, 2007).

During everyday locomotion the CNS is faced with the challenge of a changing body-environment relationship, such as when the body size changes naturally as it does with pregnancy, or when large and wide objects are being carried. In such situations, the perceptual-motor system must update the current *perceptual ruler* in order to adapt movements accordingly. In general, individuals adapt to these changes quite well. Franchak and Adolph (2007; 2014a) showed that pregnant women are able to re-scale the perceived passability of apertures to reflect the changing affordances of their growing belly: judgement thresholds (*critical point)* correlate with the changing body dimensions in the months leading up to birth. Similar effects are observed when individuals are asked to judge whether an aperture allows for safe passage while holding a horizontal bar (Wagman & Taylor, 2005). Likewise, when walking through the same aperture while holding the bar, the *magnitude of rotation* is regulated in response to the size of the bar (Higuchi, Cinelli, Greig & Patla, 2006; Higuchi et al., 2012).

Although evidence suggests that individuals are sensitive to increases in the aperture to shoulder width (A/S) ratio, the ability to adapt actions to fit this ratio may become more accurate with practice. When individuals are asked to judge the passability of an aperture while using a wheelchair, practice is required before judgements surpass a *critical point* of 1.0 and include a margin sufficient to allow for safe passage (Yu & Stoffregen, 2012; Higuchi et al., 2006). To pass through the aperture safely, participants needed to gain experience using the wheelchair in order to inform the CNS of the size of the person-plus-object system and adapt perceptual judgements and actions accordingly. This adaptation to the changing person-environment system appears to occur within one testing session. Non-pregnant participants who wore a pregnancy-pack to instantly increase the size of their bellies, made judgements and action changes that were similar to individuals who experienced the change in body size associated with their pregnancy over a longer period of time (Franchak & Adolph, 2014b). Despite the rapid changes in their bodies and the constraints that the increased body size put on crossing ability, these results highlight the ability of the CNS to quickly adapt movements according to the spatial demands created by the size of the body.

Together the aforementioned studies have contributed three major findings to the aperture crossing literature. First, the perception-action system determines the division between passable and impassable apertures based on the relationship between the shoulder width and the environment. Second, modifications to actions are made at apertures smaller than the *critical point* in order to maintain a *spatial margin* between their shoulders and the obstacles. Third, the CNS adapts perceptual judgements and actions to meet the spatial demands of the changing A/S ratio.

1.5 Overview of Thesis

When walking through an aperture on the travel path, individuals determine whether or not the aperture is passable by comparing it to the size of their body (Warren & Whang, 1987). A passable aperture is considered to be 1.3x SW or larger. Passing through apertures smaller than this ratio requires the individual to make adjustments to the current state of the moving body in order to pass through safely. Specifically, research shows that the *magnitude of rotation* produced at the TOC increases as the aperture gets smaller (Warren & Whang, 1987; Hackney et al., 2013), that adjustments to *walking speed* also follow this trend (Wilmut & Barnett, 2010) and that at the smallest aperture sizes (0.8 – 1.1x SW) individuals act to maintain a *spatial margin* of 6-10cm between the shoulders and the obstacles at the TOC (Higuchi et al., 2012).

The literature clearly demonstrates that ground-level walking through a single aperture aligned with the end-goal is well understood, however such rudimentary environments are rarely encountered in normal day-to-day life. Instead, the perception-action system is often tasked with navigating the body through cluttered environments under much more challenging circumstances. For example, in our daily lives we pass through narrow spaces while carrying objects, during instances when our ability to maintain stability is challenged, when there is more than one aperture to consider and even when that aperture is created by different types of obstacles. However, research has yet to document aperture crossing behaviour in these environments, despite the common, everyday nature of such tasks. The general purpose of this thesis was to expand on the current understanding of how individuals pass through narrow spaces by investigating aperture crossing behaviour in challenging environments and to identify how the body-environment relationship contributes to determining the affordance of aperture crossing.

This dissertation is comprised of a series of studies, each designed to target a specific aspect of aperture crossing in complex environments. The specific research questions addressed are outlined below, however relevant literature and the hypotheses for each research question will be presented in the accompanying chapter.

1.5.1 Specific Research Questions

Research has revealed that the decision to pass through an aperture is based on the size of the shoulder width (Warren & Whang, 1987). In circumstances where the shoulders are not the widest dimensions of the body, using the shoulders to judge the passability of an aperture is not advantageous and may result in a collision. Such situations occur when the width of the moving body is increased because one is carrying a wide object. The question remains as to whether individuals adjust their judgements to consider the new width of the moving body and whether the division between passable and impassable apertures (i.e., the *critical point*) is also scaled to this new size. Chapter 2 will address this question by examining aperture crossing in a person-plus-object environment. Specifically, this study aimed to identify the *critical point* while carrying objects that are wider than the body and determine whether individuals scale their actions to the size of the aperture width/shoulder width (A/S) ratio or to the aperture width/person-plus-object width (A/O) ratio.

In addition to using the shoulder width to determine whether an aperture affords passage, research has also demonstrated that individuals act to maintain a *spatial margin* between the body and the obstacle at the TOC. This behaviour has been observed in two ways. First, the fact that the *critical point* is 1.3x SW and not the exact width of the body (i.e., 1.0x SW) suggests that individuals maintain a buffer zone to account for natural sway when passing through the aperture (Warren & Whang, 1987). Second, research has also shown that rotations are initiated in an attempt to maintain a space of 6-10cm between the shoulders and the obstacles at the TOC, suggesting that the CNS determines the necessary amplitude of rotations based on a minimal *spatial margin* (Higuchi et al., 2012). Whether this body-scaled *critical point* of 1.3x SW and *spatial margin* is maintained in challenging environments remains unclear. Chapters 3 and 4 investigate this question by challenging the movement abilities of the walker (Chapter 3) and by changing the characteristics of the obstacles to be crossed (Chapter 4). Specifically, Chapter 3 investigates whether postural threat influences the size of the *critical point* and the *spatial margin* by having participants walk through apertures under three possible conditions: 1) normal ground-level walking, 2) narrow ground-level walking, or 3) elevated/narrow path walking. In Chapter 4, I investigate whether these crossing behaviours are altered when the aperture is created by other people rather than the typical cardboard or light-weight wood obstacles.

Lastly, the literature has revealed that individuals aim to walk through the center of an aperture in an attempt to equalize the amount of space between the shoulders and the obstacles at TOC (Cinelli, Patla & Allard, 2008). Whether this strategy is maintained when more than one aperture is presented on the travel path or when an aperture is off-set from the end-goal remains unknown. Chapter 5 examines this scenario by investigating the strategies that are used to walk through three separate apertures that vary in aperture size and location relative to the end-goal.

As stated above, the relevant literature and the hypotheses for each research question will be presented the respective chapters that follow.

- Chapter 2 -

IS THE CRITICAL POINT OF APERTURE CROSSING ADAPTED TO THE PERSON-PLUS OBJECT SYSTEM?

Adapted from:

Hackney, A.L., Cinelli, M.E., and Frank, J.S. (2014). Is the *critical point* of aperture crossing scaled to the person-plus-object system? *Journal of Motor Behaviour, 46* (5), 319-327.

2.1 Abstract

The passability of apertures is based on the largest horizontal dimension of the body such that individuals will either rotate their shoulders or walk around apertures that are less than 1.3x SW (i.e., *critical point*). Carrying large objects through apertures creates a person-plus-object system that constrains action capabilities and requires that the individual adapt to this increase in size. The current study aimed to determine whether the *critical point* is maintained when the horizontal dimension of the body is suddenly enlarged by carrying an object wider than the shoulders. Participants (N = 22, $\bar{x}_{\text{age}}$ = 22.8 years) walked at a self-selected pace along a 10m path and passed between or around two vertical poles placed halfway along the path. Participants performed the task without or while holding a serving tray that was either 1.2, 1.4 or 1.6x wider than their SW. The distance between the poles was scaled to be 1.0 - 1.6x each participant's widest dimension (shoulder or tray width) in increments of 0.2. Results identified two distinct responses to carrying the tray: "the affected" and "the unaffected". "The unaffected" (n = 12) maintained their *critical point* throughout the experiment and approached the obstacles at the same velocity regardless of whether the tray was carried. "The affected" (n = 7) initially increased their *critical point* and reduced their *approach velocity* when carrying the tray, before returning back to their baseline value by the end of the experiment. The results suggest that individuals can account for increases in body width by scaling actions to the size of the object width but that adaptation may occur at slightly different rates.

2.2 Introduction

During everyday locomotion it is likely that an individual will encounter a narrow space, such as a blocked doorway or two closely parked vehicles, while en route to their goal. In such situations, the individual is faced with three options to reach their goal successfully: (a) walk straight through the space, (b) pass through the gap and rotate the shoulders, or (c) avoid the aperture all together by walking around it. When choosing the appropriate action, one must be able to identify whether or not the aperture is passable (i.e., its affordance must be identified). Affordances are defined as the opportunities for action for a given organism based on the relationship between the dimensions of an object and the dimensions of the observer (Adolph & Berger, 2006; Gibson, 1979; Warren, Young, & Lee, 1986). This means that dimensions of objects within the environment are determined based on body-scaled information (Fajen, 2013). For instance, the ratio between the length of the leg and riser height on stairs specifies whether it is or is not climbable (Warren, 1984) and the ratio between the shoulder width and aperture width determines whether an aperture can be crossed with or without a change in shoulder position (Warren & Whang, 1987). When the difference between the size of the object and the size of the individual reaches a point where the observer changes his or her action, the ratio at which this change occurs is identified as the *critical point* (Warren, 1984).

Since decisions for actions are based on the ratio between the size of an object and the size of the body, the perceptual-motor system must continuously update knowledge of this ratio in order to adapt movements to the ever-changing environment. This becomes especially challenging when the ratio changes, such as when the size of a gap dynamically changes or the size of the body is altered. It is well documented that young adults (YA) are sensitive to small changes in the width of an aperture and that their perceptual system can quickly and efficiently inform the action system of such changes in order to produce an appropriate response (Higuchi et al., 2006). As such, individuals can distinguish between passable and impassable apertures both while making perceptual judgements about the passability of an aperture and when actually walking through them (Franchak et al., 2010). Additionally, Wilmut and Barnett (2010) demonstrated that the *magnitude of shoulder rotation* at the TOC is inversely proportional to the size of the aperture, such that larger shoulder rotations are produced for smaller aperture sizes. Similarly, when walking around an aperture (rather than walking through it), the size of the path deviation from midline increases as the size of the aperture increases (Hackney et al., 2013). This apparent sensitivity to changes in the A/S ratio extends beyond alterations to the size of the environment, as previous literature suggests individuals are also capable of updating this relationship when the size of the body changes, as is the case when carrying large objects (Higuchi et al., 2006; Stefanucci & Geuss, 2009; Wagman & Taylor, 2006).

Carrying objects that are wider than the body creates a person-plus-object system that limits an individual’s ability to pass straight through small spaces without rotating the shoulders. In order to pass through an aperture safely, the affordance for crossing must relate to the width of the person-plus-object and not the width of the individual (Bongers, Michaels, & Smitsman, 2004; Wagman & Carello, 2003). Previous work has demonstrated that individuals adapt quite well to such changes in their body dimensions when asked to pass through narrow spaces. Wagman and Taylor (2005) had YA hold either a large horizontal pole or two horizontal objects (one in each hand) while making a yes or no perceptual judgement about whether an aperture allowed for safe passage. In both scenarios, the boundary between passable and impassable apertures increased to account for the size of the object being carried. If participants were asked to hold a large horizontal bar and actually walk through the apertures, the *magnitude of shoulder rotations* was regulated in response to the size of the bar: individuals turned more to account for the larger M-L dimension (Higuchi et al., 2006; 2012). Franchak & Adolph (2007, 2014a) provided further evidence for such adaptation by showing that pregnant women were able to adapt both their actual threshold and judgement thresholds about the passability of an aperture to their increasing body size which suggests not only that both the perceptual system and action system can account for changes in the A/S ratio, but that these adaptations occur quite quickly. Furthermore, this ability to adapt actions to fit the A/S ratio appears to become more accurate with practice (Franchak et al., 2010; Mark et al., 1997; Mark et al., 1990; Stoffregen, Yang, Giveans, Flanagan, & Brady, 2009; Yasuda, Wagman, & Higuchi, 2014; Yu & Stoffregen, 2012). Together, these results suggest that individuals are indeed sensitive to the A/O relationship in relation to a person-plus-object system.

Although the literature suggests that YA adapt their aperture crossing behaviour to account for changes in body size when carrying wide objects, such as how much they rotate and how much they slow down, the *critical point* has not been explicitly examined to determine whether it is scaled to the size of the person-plus-object system. Therefore, the purpose of the present study was two-fold: (a) identify whether the *critical point* is scaled to the A/O ratio and (b) determine whether adaptation to the A/O size occurs instantly or whether it evolves with repeat exposure. Fajen (2013) postulated that the body-scaled information required to identify the passability of apertures stems from the individual’s knowledge of the relation between his or her body size and eye height (i.e., the constant ratio between the width of the shoulders and the distance the eyes are from the ground). It is argued that this relationship is learned through active exploration, which is then used to form an accurate perception of the size of the environment in relation to the size of the body. Fajen (2013) suggested that in the event that either eye height or body size is altered, the perceptual-motor system must recalibrate itself to accommodate for these changes. By altering the size of the body (but not the eye height), the present study will test whether individuals can adapt their actions to accommodate for the change in the relationship between body size and eye height and identify how much active exploration is required to make this adjustment. Since the literature suggests that individuals can quickly rescale perceptual judgements to account for increases in body size (Franchak et al., 2010; Stefanucci & Guess, 2009; Wagman & Taylor, 2006), that perceptual judgements about the passability of apertures matches actions (Franchak & Adolph, 2007; Hackney & Cinelli, 2013a) and that individuals strive to maintain a similar-sized *critical point* across different environmental contexts (Hackney & Cinelli, 2013b; Warren & Whang, 1987), it was hypothesized that individuals would quickly adapt to carrying the object by maintaining a similar-sized *critical point* regardless of whether the object was carried.

2.3 Methods

2.3.1 Participants

Twenty-two healthy YA ($\bar{x}_{\text{age}}$ = 22.8 ± 1.5 years; 13 females, 9 males) ranging SW from 34 to 54 cm ($\bar{x}_{\text{width}}$ = 43.5 ± 4.4cm) volunteered to participate in the experiment (Table 2.1). Participants were included in the study if they were free of deficits or disorders that could affect postural control, balance and locomotion, if they conveyed no self-reported history of hip, knee, or ankle injury; had normal or corrected-to-normal vision; and could understand English instructions. Upon arrival, participants completed a screening questionnaire (Appendix B) to ensure qualification for the study. Height and SW were measured by the researcher using a measuring tape and recorded to the nearest half centimeter.

The experimental protocol was approved by the Wilfrid Laurier University Research Ethics Board and Office of Research Ethics at the University of Waterloo. All participants gave their informed consent prior to participating.

Table 2.1 – Participant characteristics, including gender, height, SW and *critical point* for the No Tray condition, grouped by adapter type (see Results section 2.4.2).

Adapter Type	Participant	Initial CP (No Tray)	Gender	Height (cm)	SW (cm)
Fast	1	1.2	F	170.0	39.0
	2	1.4	F	155.5	34.0
	3	1.2	M	196.0	43.5
	4	1.4	M	179.0	50.0
	5	1.2	F	167.5	42.0
	6	1.2	F	164.5	43.0
	7	1.2	F	162.0	38.5
	8	1.2	M	185.0	47.0
	9	1.3	F	173.5	39.5
	10	1.2	M	173.5	45.0
	11	1.3	M	182.0	48.0
	Average/SD	***1.25 ±0.08***	**--------**	***173.5 ±11.5***	***42.6 ±4.7***
Slow	12	1.2	F	170.0	46.5
	13	1.2	M	186.0	46.5
	14	1.2	F	164.5	41.5
	15	1.4	F	170.5	40.0
	16	1.4	F	170.5	44.0
	17	1.2	F	167.5	40.0
	18	1.2	M	188.5	54.0
	19	1.3	F	158.5	47.0
	Average/SD	***1.26 ±0.09***	**--------**	***172 ±10.2***	***44.9 ±4.6***
Non-adapters	20	1.3	M	176.5	46.0
	21	1.4	M	170.0	44.5
	22	1.4	F	161.0	43.0
	Average/SD	***1.35 ±0.06***	**--------**	***169.2 ±7.7***	***44.5 ±1.5***

2.3.2 Apparatus

Similar to previous work (Hackney & Cinelli, 2013b; Hackney et al., 2013), the experiment was conducted in a 10m (L) by 6m (W) path with two vertical pole obstacles (0.23m W x 2.4m H) located half way down the path on either side of the midline (Figure 2.1a). The position of the obstacles created an aperture between the poles that ranged from 1.0 to 1.6x SW in increments of 0.2. The subset of aperture widths in the present study were chosen to present the participants with widths that were both smaller and larger than the previously reported *critical point* (1.3) in order to determine whether the value increased or decreased throughout the experimental conditions. Furthermore, the range of aperture widths was chosen to ensure that at least one condition would elicit a shoulder rotation 100% of the trials and another would result in no shoulder rotation 100% of the trials (1.0 and 1.6 respectively). During a subset of the testing conditions, participants carried an adjustable serving tray that was made of lightweight plastic. The tray was 35cm wide and could be adjusted to range between 40 - 95cm in width (Figure 2.1b).

Kinematic data was measured using the OptoTrak camera system (Northern Digital Inc., Waterloo, Canada) at a sampling frequency of 60Hz. Rigid bodies were placed on the external occipital protuberance and left scapula to allow for the left/right ears and the left/right posterolateral aspects of the spinous processes of the scapula and T10 to be digitized (Appendix C).

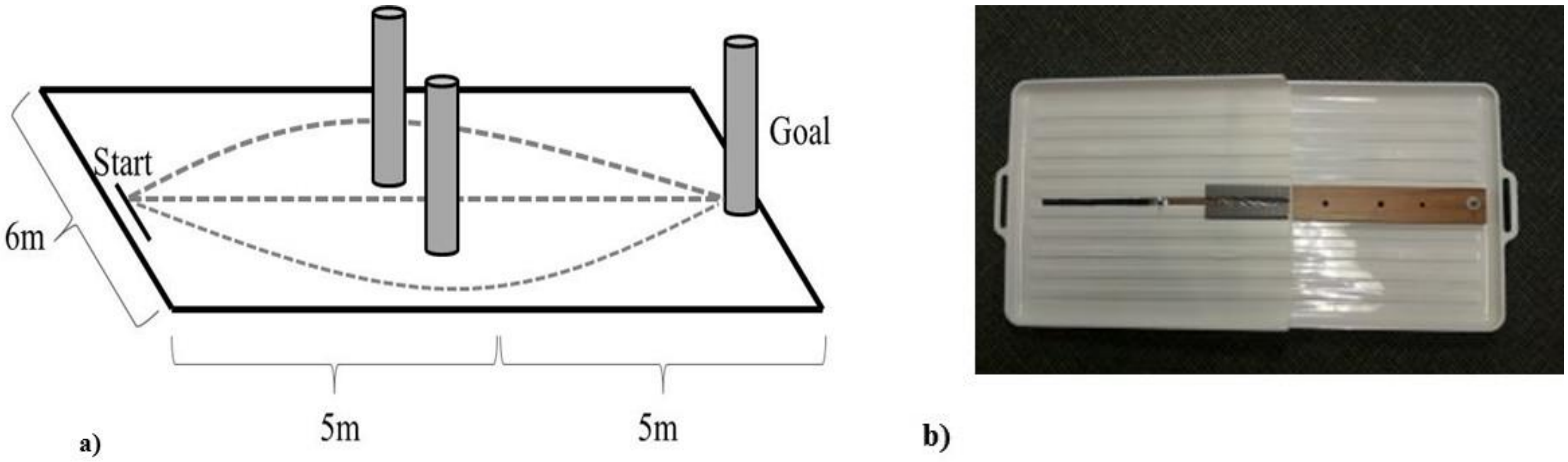

Figure 2.1 - a) A sagittal view of the experimental set up including an outline of the three paths available to get to the goal, and **b)** an aerial view of the light-weight, adjustable serving tray carried for a subset of the trials.

2.3.3 Design

The experiment consisted of four blocks of trials. In the first block, the participants were asked to complete the trial normally (i.e., walk to the end-goal without colliding with the obstacles), without carrying a tray. This block was referred to as the No Tray condition. Participants also completed three blocks of trials while carrying the adjustable serving tray. Each block included one of three tray lengths which were determined based on each participant's shoulder width: 1.2, 1.4, and 1.6x SW. These tray-carrying blocks of trials were referred to as Tray 1.2, Tray 1.4, and Tray 1.6, respectively. The experiment followed a pseudorandomized design such that the No Tray block was completed first, followed by a randomized order of the three tray blocks of trials.

When participants walked along the path, an aperture was presented half way between the starting location and the goal. The aperture ranged in width from 1.0 – 1.6x the SW in increments of 0.2. It is important to note that the aperture widths were determined based on the size of the shoulder width or the size of the tray, depending on the current condition. Therefore, during the No Tray condition, the four aperture widths were calculated relative to the size of the participants shoulder width, while in the three tray conditions the aperture was determined based on the size of the tray being carried.

2.3.4 Procedure

On all experimental trials, participants were instructed to walk at their natural pace toward the goal located at the end of the path and avoid coming in contact with the two obstacles that created the aperture. Direct instructions were not provided as to how to avoid the obstacles as we wanted participants to be able to choose behaviours that they would do in a more natural setting.

Prior to the start of each trial, the participants turned away from the aperture by facing in the opposite direction of travel while the experimenters manually adjusted the position of the obstacles to marked locations on the ground. The experimenters confirmed the width of the aperture with a measuring tape to the nearest half centimeter. Participants took a mandatory five minute break following each block of trials and could voluntarily take a break at any point during the experiment.

Each trial began in one of three randomly assigned starting locations, each which were separated by 15cm in the direction of travel (i.e., A-P direction). The randomized starting position was used to help reduce an individual's reliance on a consistent number of steps before initiating a change in their behaviour (e.g., always taking ten steps before deviating off the straight walking path).

2.3.5 Data and Statistical Analysis

The COM location in the M-L and A-P direction were estimated using the three IRED markers placed on the torso (Appendix C). This approach was adapted from Winter and colleagues (1998) and reported in previous work (Hackney & Cinelli, 2011; Hackney et al., 2013). It is worth noting that for the purpose of this study, the term *critical point* was defined as the threshold between passable and impassable apertures. Since participants were instructed to avoid contacting the obstacles but were not restricted to walking only through the aperture (i.e., they could choose to walk around the aperture), impassable apertures were considered those in which an individual voluntarily chose to rotate his or her shoulders while passing through the aperture or ones where they avoided passing through the aperture all together by walking around it. This study used the calculation of the *critical point* to determine whether adaptation to increases in the width of the body had occurred on an individual basis by comparing the individual *critical point* of every participant during each tray condition to that of their No Tray condition *critical point.*

On an individual basis the proportion of straight walking trials for each participant was documented. This was determined by the *M-L COM position at TOC*. Values close to zero represented trials where the individual walked straight through the aperture, while positive or negative values represented a path deviation to the right or to the left of the obstacles, respectively. Trials where participants walked straight through the aperture were then analyzed for significant shoulder rotations. Similar to previous reported analyses (Hackney & Cinelli, 2013b; Wilmut & Barnett, 2010), shoulder rotation angles were calculated using the two IRED markers on the left and right shoulders (Appendix A). A shoulder rotation was identified if the *magnitude of rotation* fell outside two standard deviations of the average rotation during the approach phase. The approach phase began after the third step and continued until the A-P COM was 1.5m from the aperture. Trials where no shoulder rotation occurred were scored with a zero and trials where the participant rotated the shoulders or where he or she walked around the aperture were given a score of one. Therefore each participant was assigned a proportion of straight walking trials for each aperture width within a given block of trials. A participant's individual *critical point* was defined as the largest aperture width where at least 60% of the trials resulted in either a shoulder rotation or a change in path trajectory. This process was repeated for each of the four testing conditions and allowed the researchers to identify if or when adaptation occurred on an individual basis. As a reminder, both a change in shoulder position and a change in travel path were considered to be actions associated with an impassable aperture width since we set out to determine the size of aperture that elicits a change from straight walking.

The proportion of trials where a change in action occurred across all participants was run through a Friedman's nonparametric analysis of variance (ANOVA) to determine whether the proportion of impassable apertures was affected by the size of tray or by the order in which the tray sizes were presented. For trials where a shoulder rotation occurred, one-way repeated measures ANOVAs were also used to determine whether the *magnitude of rotation* was affected by the tray size or order of presentation.

Other aperture crossing behaviours such as the *approach velocity*, *M-L COM position at TOC*, *spatial margin*, and *trunk sway* were calculated using the COM. *Approach velocity* was defined as the average walking speed, the change in displacement of A-P COM over time, during the approach phase. *M-L COM position at TOC* was defined as the position of the M-L COM when the A-P COM crossed the aperture. M-L *trunk sway* during the approach phase was determined by calculating the absolute angle between the IRED marker at T10 and a calculated imaginary point between the two shoulder markers. Lastly, the *spatial margin* was determined by finding the absolute distance between the inner edge of the obstacle and the shoulder at TOC. Appendix A provides a visual representation of the dependent variables analyzed in this study.

The abovementioned dependent variables were assessed using a 4 (aperture width) x 4 (tray size) general linear model (GLM) with repeated measures. *P*-values less than 0.05 were accepted as significant and Tukey's post-hoc analyses were used when appropriate.

2.4 Results

2.4.1 Avoidance Strategies

All participants successfully avoided colliding with the obstacles throughout the entire experiment and completed the task in one of three ways: (1) walk through the aperture with no shoulder rotation, (2) walk through the aperture while rotating the shoulder, or (3) avoid the aperture by walking around the obstacles. The proportion of trials where these three behaviours occurred for each condition is displayed in Figure 2.2. During the No Tray condition, the predominant strategy was to walk straight through the aperture without producing a shoulder rotation and to rotate the shoulders at the smaller aperture sizes. However during the three tray conditions, rather than rotate the shoulders for impossible apertures, individuals avoided the aperture by walking around it. Since the production of a shoulder rotation was the dominant strategy used to walk through smaller apertures in the No Tray condition, the proportion of shoulder rotations was used to calculate the individual *critical point* for this block of experimental trials. However, since shoulder rotations did not occur while carrying the tray (likely due to restrictions in the depth of the tray), the proportion of avoidance trials was used instead to determine each participant's *critical point* for the remaining tray conditions.

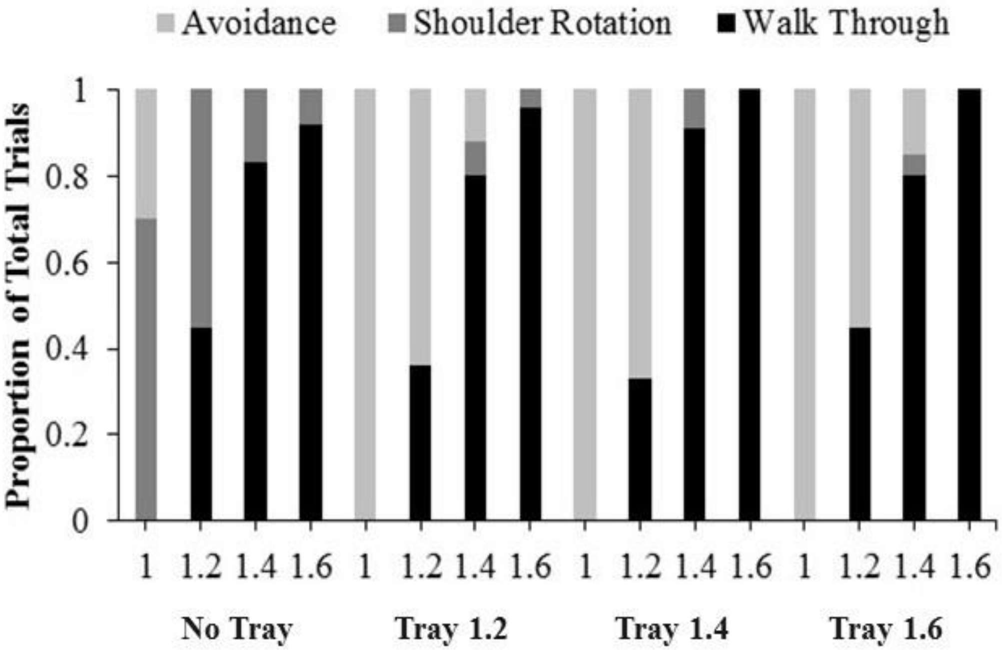

Figure 2.2 – The proportion of trials where participants walked straight through, rotated the shoulders or walked around the aperture. Participants predominantly rotated their shouldres for apertures deemed to small for straight passage when the tray was not carried but walked around the aperture when carrying the tray.

Friedman's non-parametric ANOVAs revealed a significant effect of aperture width for the No Tray ($\chi^2_{(4, N = 22)} = 63.28$, $p < 0.001$); first tray ($\chi^2_{(4, N = 22)} = 65.63$, $p < 0.001$); second tray, ($\chi^2_{(4, N = 22)} = 67.34$, $p < 0.001$); and third tray exposures ($\chi^2_{(4, N = 22)} = 66.95$, $p < 0.001$). Post hoc analysis for each condition was conducted using Wilcoxon signed rank tests and compared aperture widths 1.2, 1.4, and 1.6 to the proportion of straight walking trials at aperture 1.0. The aperture width 1.0 (the width that was equal to the size of the shoulders) was used for comparison because it represented the condition at which the percentage of straight walking trials was zero. As participants never walked straight through this aperture width, it could be used to determine the aperture width where a significant proportion of straight walking trials first started to occur. Results revealed that the proportion of straight walking trials at apertures 1.2, 1.4, and 1.6 significantly differed from that at aperture 1.0 in the No Tray condition ($p < 0.05$ for all comparisons). Conversely, in the three tray conditions the proportions only differed significantly from 1.0 at apertures 1.4 and 1.6 ($p < 0.05$ for both). Therefore, there appeared to be an effect of tray size, where participants voluntarily walked around larger relative aperture widths while carrying the tray compared to when the tray was not carried, however the size of the tray did not influence the frequency of avoidances (Figure 2.3a). Additionally, a significant effect of presentation order existed ($\chi^2_{(3, N = 22)} = 10.81$, $p < 0.05$), where the proportion of avoidance trials for the first encounter with the tray was significantly higher than all other conditions ($p < 0.05$, Figure 2.3b).

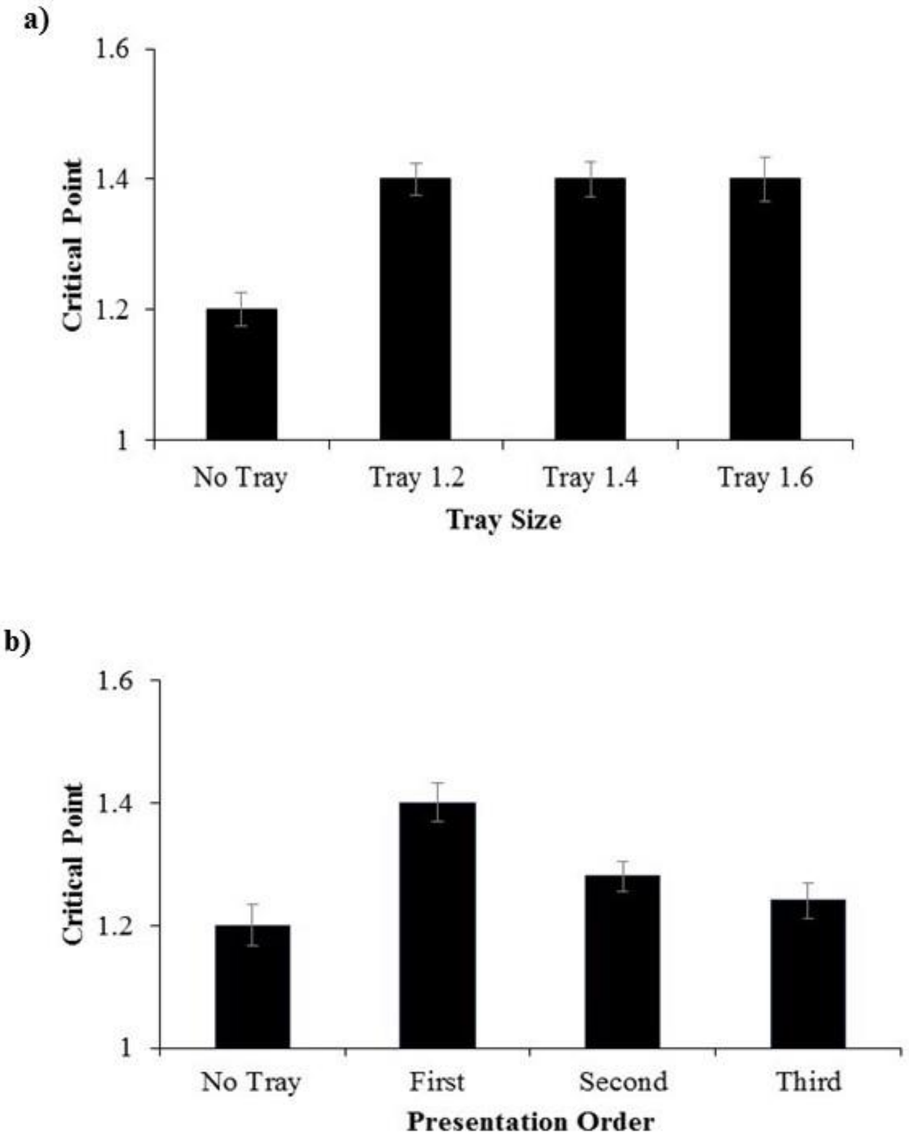

Figure 2.3 – a) *Critical point* for each block of trials based on the size of the tray. *Critical point* increased when the tray was carried ($p<0.05$), and **b)** Group *critical point* for presentation order. The *critical point* was largest the first time the tray was carried ($p<0.05$).

On trials where the participants chose to walk around the aperture, the *M-L COM position at TOC* was affected by the aperture width ($F_{(3, 54)} = 29.02$, $p < 0.001$, $\eta^2 = 0.63$), where participants deviated farther from the midline of the path as the aperture increased in size. The results also demonstrate that M-L position was significantly affected by tray size ($F_{(3, 54)} = 13.78$, $p < 0.001$, $\eta^2 = 0.43$) such that deviations from the midline were larger as the size the tray increased. The presentation order did not affect the position of the COM.

2.4.2 Adaptation Rates

To determine whether adaptation occurred, the *critical point* in the No Tray condition was compared to the *critical point* in the final exposure to the tray for each participant. Adaptation was deemed to have occurred if the difference between the two conditions was zero. Three participants had a difference greater than zero and were therefore considered the “non-adapters” while the remaining nineteen participants adapted as hypothesized. The three “non-adapters” were removed from further analysis, while the adapters were analyzed for speed of adaptation. The “non-adapters” were removed from all further analyses because these participants each had an initial *critical point* (in the No Tray condition) that fell well outside the norm in previously reported studies (*critical point*s of 1.6 or larger). These participants walked around every aperture width presented to them (Table 2.1). Retrospectively, when asked why they chose to always walk around the aperture, these participants responded that they thought they were supposed to walk around the poles every time.

To determine how quickly participants adjusted to the tray, the individual *critical point* for the first, second and third exposures were examined. If the slope of the line across conditions was maintained at zero (i.e., the same *critical point* throughout the entire study), the participant adapted to the tray within the first exposure. These participants were grouped together and identified as the “unaffected” (n = 11) as their behaviours were not altered by increases in body size when holding the tray (Figure 2.4). If the slope was negative, the participant was characterized as a “the affected” (n = 7; Table 1). These participants displayed a larger *critical point* during the first block of trials in which they were required to carry the tray (average increase from 1.25 to 1.51). A negative slope indicated that the *critical point* was higher in the first and second tray exposures before returning to the original value; warranting the “the affected” name (Figure 2.4). It is important to note that “the affected”” were still able to adapt to the increase in body size, they just appeared to do so at different rates.

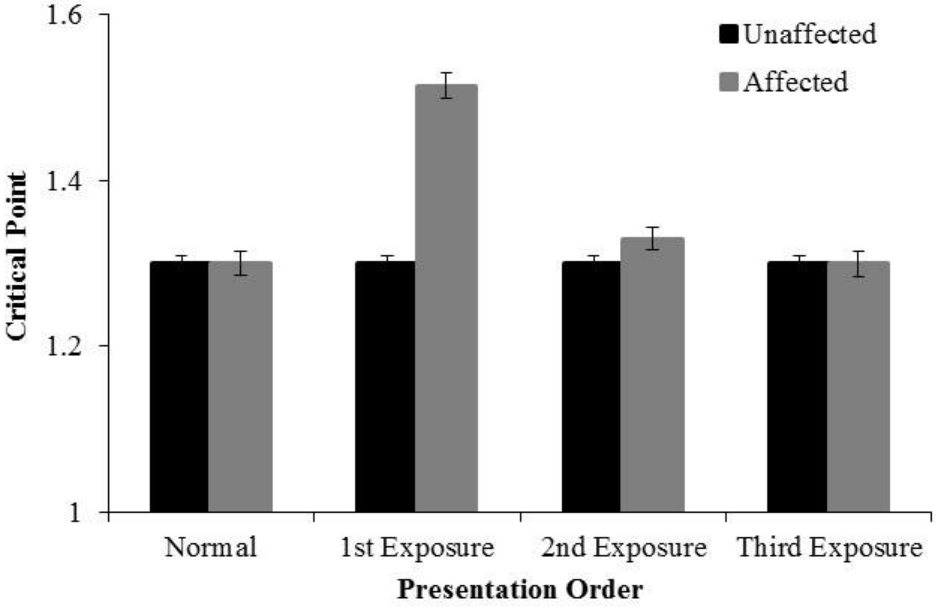

Figure 2.4 – The group *critical point*, split by adapter-type based on presentation order. “The affected” increased their *critical point* the first time they carried the tray while “the unaffected” maintained the same *critical point*.

2.4.3 Other Aperture Crossing Behaviour

Aperture width was shown to have an effect on *approach velocity* ($F_{(4, 69)} = 4.97$, $p < 0.05$, $ŋ^2 = 0.26$), where participants decreased their walking speed as the aperture size decreased. Unlike path trajectory however, block (No Tray vs. tray), tray size, and presentation order did not affect *approach velocity*. Similarly the *trunk sway* and *spatial margin* were not affected by aperture width, testing condition, and tray size or presentation order. When these variables were compared between “the unaffected” and “the affected” with a 4 (aperture width) x 4 (tray size) x 2 (adapter type) GLM, only *approach velocity* demonstrated differences between groups ($F_{(1, 17)} = 4.82$, $p < 0.05$, $ŋ^2 = 0.29$). Tukey’s post-hoc analysis revealed that “the affected” displayed a decrease in their walking speed when carrying the tray compared to when the tray was not carried ($p < 0.05$) while the “unaffected” maintained the same speed throughout the study regardless of condition (Table 2). *M-L COM position at TOC*, *trunk sway* and *spatial margin* did not differ between groups.

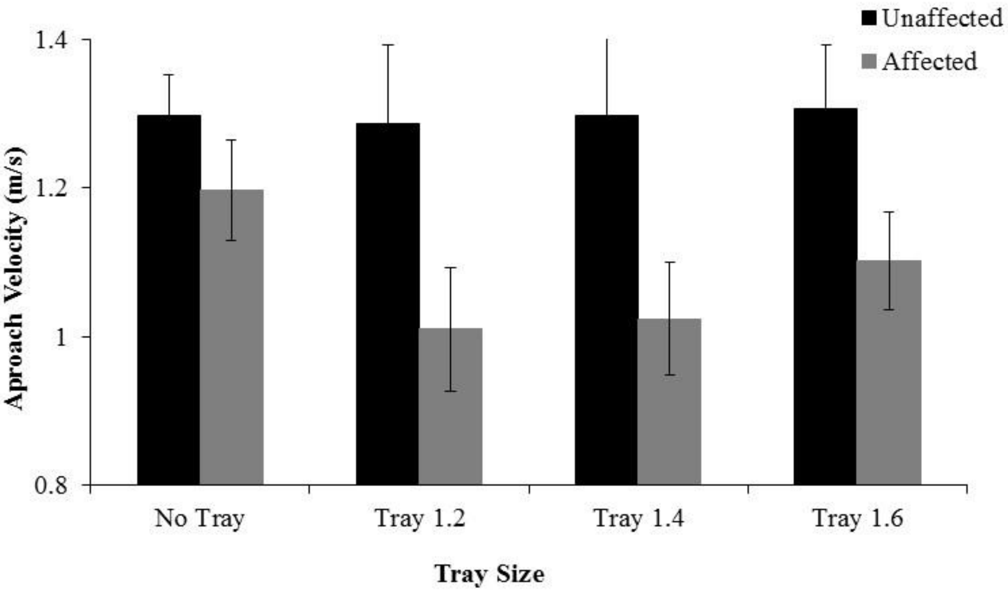

Figure 2.5 – Average *approach velocity* for each block of trials based on the size of the tray, split by adapter-type. “The affected” walked slower when carrying the tray compared to “the unaffected” ($p<0.05$).

2.5 Discussion

In the current study we set out to determine whether individuals scale the *critical point* to the person-plus-object system when walking through apertures. We hypothesized that adaptation would occur quickly when carrying an object that was wider than the shoulder width by maintaining a similar relative *critical point* when the tray was carried compared to when it was not. As hypothesized, the results demonstrate that individuals can indeed adapt to the person-plus-object system in order to maintain a consistent *critical point*. This was evident from the similarities of the *critical point*s between the No Tray and final tray exposure (Figure 2.3b). However unlike the hypothesis, the adaptation did not always occur within the first exposure to the tray (Figure 2.3b). Although the results originally revealed that the *critical point* during each of the three tray conditions was larger than that of the No Tray condition (1.4 and 1.2, respectively; Figure 2.3a), the effect disappeared when considering the order of exposure. The increased *critical point* only occurred during the first block of tray trials (Figure 2.3b), which was marked by considerable variability across participants. However, the group *critical point* did return to the No Tray value by the final tray exposure.

The larger *critical point* at the first tray exposure is contrary to our hypothesis, as it was predicted that individuals would adapt the *critical point* within the first exposure. This result, coupled with the considerable variability within each condition prompted individual analysis of adaptation rate to determine whether all participants followed this trend. Since all participants adapted their *critical point* by the final tray exposure to match that of the No Tray condition, the slope of the line across the three tray conditions provided insight into the rate of adaptation. A subset of the participants (n = 7; “the affected”) increased their *critical point* the first time they experienced the person-plus-object system (carrying the tray) but returned to their original *critical point* during the second and third exposures while the remaining participants (n = 12) maintained the same *critical point* throughout the entire experiment (“the unaffected”).

The fact that the present study identified two distinct types of adapters to the person-plus-object system was an unexpected but novel finding. Previous research suggests that individuals can correctly perceive affordances of objects by means of dynamic touch (Carello, 2004; Carello & Turvey, 2004; Stefanucci & Geuss, 2009; Wagman & Taylor, 2005), by means of vision (Hackney & Cinelli, 2011; Higuchi et al., 2006; Warren & Whang, 1987) and the manner in which an object constrains affordances for locomotion for a person-plus-object system (Higuchi et al., 2006; Higuchi et al., 2012; Wagman & Taylor, 2005). Therefore, it was reasonable to hypothesize that the travel path selections in the present study would be scaled to the size of the aperture. However, only “the unaffected” in the present study provide support for the evidence that these adjustments also occur for actions (Higuchi et al., 2012). The unexpected finding that a second group of participants (“the affected”) took time to adapt to the increase in body size suggests that not all individuals adjust to changes in body dimensions at the same rate.

Previous work has suggested that perceivers must spend time exploring the perception-action dynamics of the person-plus-object system in order for the perceived boundaries of behaviour to match the action capabilities of the system (Franchak et al., 2010; Hirose & Nischio, 2001; Mark, 1987; Mark et al., 1990). Research has demonstrated that novel wheelchair users are sensitive to the increased body width that a wheelchair creates; however, practice was required before the judgements surpassed the boundary of 1.0 and included a *critical point* sufficient to allow for safe passage (Higuchi et al., 2006; Yu & Stoffregen, 2012). In order to pass through the aperture safely, participants needed to gain experience using the wheelchair in order to inform the CNS of the size of the person- plus-object system. Similarly, research has shown that perceived boundaries for aperture crossing with large objects are underestimated compared to when the object is not held. Perceived boundaries when carrying the object was slightly smaller than the A/S ratio of 1.0, suggesting that participants rely on online regulation of perceptually guided behaviour to make specific adjustments to actions (Wagman & Carello, 2003). Although the actions of "the affected" in the current study were indicative of an overestimation (rather than an underestimation), as evident through a larger *critical point*, the differences in behaviour between the present and previous work may be a result of differences in the task. The overestimation in the present study may have been used to ensure that a collision with the aperture did not occur: underestimations of the passability of a space may have resulted in injury if the participant collided with the obstacles. The underestimations reported in previous work were observed when participants were asked to determine whether they could fit through an aperture using a yes or no response. Participants were not asked to walk through the aperture and therefore, an underestimation posed no risk of injury or failure to the participant.

As previous work has shown that novel wheelchair users require time to adjust their actions to the size of the chair (Higuchi et al., 2006), it is also possible that the "the affected" just needed time to gain experience carrying the tray. Although it is possible that these particular participants were completely novel tray carriers, experience with tray carrying was likely not a factor for differences in behaviour as both groups of participants reported that they were not, and had never been servers. Additionally, there was no evidence that the two groups approached the task differently: path trajectory and lateral *trunk sway* were not different between the groups.

It is interesting that both adapter types displayed similar actions (i.e., path trajectory and *trunk sway*) during the task. When the tray was carried and the aperture was deemed too small for straight walking both groups opted to walk around the aperture. Meanwhile, when not carrying the tray, both groups chose to rotate their shoulders for impassable apertures. This is likely because the tray elicited a restraint on the participant's action capabilities, making it difficult to produce a shoulder rotation. Normally a shoulder rotation is used to decrease the horizontal dimension of the body (Warren, 1984); however when the tray is carried and the body is turned, the depth of the tray adds to the width of the person and results in less a beneficial decrease in the horizontal dimension. The fact that both the "affected" and "unaffected" groups acted similarly with respect to the type of avoidance elicited, maintained similar path trajectories and had similar *trunk sway* suggests that the differences in adaptation rate between the two groups was likely not the result of the participants approaching the task differently.

The increased *critical point* of the "affected" suggests a more cautious behaviour, as these participants left more space between themselves and the obstacles when passing through the aperture during the first tray-carrying condition. It is possible that this increased caution was a result of a decrease in confidence in their ability to complete the task successfully. As the behaviour of the "affected" was unexpected, measures of confidence levels could be beneficial in understanding the differences in adaption rates between the two groups. However, these measures were not assessed and therefore a complete understanding of whether confidence played a role in one’s behaviours was beyond the scope of this study. However, analysis of *walking speed* may provide some insight into whether the “the affected” were more affected by the tray than “unaffected”. Original analysis revealed that participants approached the aperture at a slower velocity for smaller apertures compared to larger ones. This result is not surprising as previous research has shown that reductions in *walking speed* are scaled to the size of the aperture (Wilmut & Barnett, 2010). *Walking speed* did not appear to be affected when carrying the tray; however when approach speeds were separated into the two groups; the “affected” displayed a decrease in their *walking speed* when carrying the tray, while the “unaffected” maintained the same speed throughout the study. Reducing *walking speed* has been suggested to be a cautious behaviour observed in the older adult population (Nutt, 2001) as either a means of increasing the amount of time the visual-motor system has to process information and produce an appropriate response (Cinelli et al., 2009) or as a protective mechanism to minimize injury if a collision were to occur (Wilmut & Barnett, 2010). If “the affected” were more affected by the tray in terms of confidence, they might have opted to slow down in order to take more time to process information and make a decision about whether the aperture was passable or to reduce the chance of injury. Future researchers should consider analyzing confidence levels in order to identify whether confidence could in fact play a role in the rate at which the *critical point* is scaled to the person-plus-object system.

2.6 Conclusion

The results of the current study support previous work indicating that individuals adapt actions to meet the changing demands of the body dimensions when walking through narrow spaces. However our results identified two distinct responses to carrying the tray: the “affected” and “unaffected”. The “unaffected” (n = 12) maintained their *critical point* throughout the study and approached the obstacles at the same velocity regardless of whether the tray was carried. The “affected” (n = 7) initially increased their *critical point* when carrying the tray and reduce their *approach velocity* when carrying the tray. The results suggest that individuals can account for increases in body width by scaling actions to the size of the object width but adapt at different rates.

- Chapter 3 -

THE EFFECTS OF NARROW AND ELEVATED PATH WALKING ON APERTURE CROSSING

Adapted from:

Hackney, A. L., Cinelli, M. E., Denomme, L. T., & Frank, J. S. (2015). The effects of narrow and elevated path walking on aperture crossing. *Human Movement Science*, *41*, 295-306.

3.1 Abstract

Whether an aperture affords passage depends on the size of the body. Research involving older adults (OA) has suggested that the passability of an aperture may also depend on one's action capabilities, such as stability. The current study investigated how manipulations of postural threat in YA influences the passability of apertures. Participants walked along a 7m path and passed through an aperture located halfway to the end-goal. In the baseline conditions, participants walked on a ground-level path and passed through five aperture widths (1.1 - 1.5x SW). Performance in this condition determined a participant's "normal" *critical point*. Next, postural threat was manipulated by walking on a narrow, ground level path (20cm W) or an elevated/narrow path (20cm W x 40cm H). Participants completed five trials where the width of the aperture was equivalent to their "normal" *critical point*. The aperture widths to be presented in the experimental trials that followed were determined based on the behaviour during the previous five trials. This individualized approach was used to determine whether an individual's *critical point* changed in the experimental trials and to identify the specific value of the new *critical point.* Results revealed that despite a decrease in *walking speed* and an increase in *trunk sway* in both experimental walking conditions, the passability of apertures was only affected when the consequence of instability was the greatest (i.e., on the elevated/narrow path). Individuals maintained a larger *critical point*, by rotating their shoulders for larger apertures, compared to normal walking. This effect was not observed for the narrow path walking, suggesting that the level of postural threat was not enough to impose changes to the *critical point*. Therefore, it appears that manipulating action capabilities does indeed influence aperture crossing behaviour, however the consequence associated with instability must be high before both gait characteristics and the affordance of aperture crossing are affected.

3.2 Introduction

When narrow spaces are encountered along the travel path, individuals are able to quickly and accurately distinguish whether or not the aperture is passable. If the space is considered impassable, modifications to the configuration of the body are made in order to maintain a *spatial margin* between the body and the obstacles at the TOC. When specifically asked to pass through a narrow space without making any contact with the obstacles, a shoulder rotation is produced for spaces smaller than 1.3x SW but no adjustments are required for spaces larger than this value (Warren & Whang, 1987). The threshold between passable and impassable spaces (no rotations required vs. rotations required) is referred to as the *critical point* for aperture crossing and suggests that individuals consider the size of their body when passing through apertures (Hackney et al., 2013; Warren & Whang, 1987; Wilmut & Barnett, 2010). It is not surprising that the *critical point* is scaled to the size of the widest horizontal dimension of the body since a large body of literature has demonstrated that action selection is scaled to body dimensions. For example, climbable and non-climbable stairs are scaled to length of the leg (Warren, 1984), walking under barriers is scaled to height (Franchak et al., 2012) and reaching ability is related to arm length (Mark et al., 1997). However, body dimensions are likely not the only contributing factor influencing action selection such as the *critical point*, especially since individuals leave a *spatial margin* between their body and the obstacle (meaning the *critical point* is larger than the size of the body).

A number of studies have recognized the role that action capabilities and limitations to movement play on determining the possibilities for action (Choi & Mark, 2004; Fajen, 2007; Fajen, 2013; Fajen, Diaz & Cramer, 2011; Hackney, Cinelli, & Frank, 2014; Higuchi et al., 2011; Oudejans, Michaels, Bakker, & Dolne, 1996; Wagman & Malek, 2007; Wagman & Taylor, 2005). Such capabilities and limitations may include but are not limited to stability, walking speed, range of motion, strength and restrictions on action choices (such as when carrying large objects). Research examining the role of action capabilities has demonstrated that choosing whether a gap between traffic is passable is partially related to the individual's walking ability (Fajen & Matthis, 2011). Similarly, Higuchi and colleagues (2006) found that when the form of locomotion was different from that of normal walking, such as during wheelchair use or when movement restrictions are applied (i.e., no shoulder rotations permitted), individuals approach the task differently. Specifically, participants move towards the aperture at a much slower speed and collide with the obstacles more often under conditions that limit action abilities compared to normal walking (Higuchi et al., 2006). Furthermore, research with aging populations who demonstrate greater instability and slower *walking speed*s when approaching an aperture shows that OA maintain a larger *critical point* compared to their younger counterparts even when body size was accounted for. Older adults have an average *critical point* of 1.6, while YA maintain a consistent 1.3x SW (Hackney & Cinelli, 2011). This larger *spatial margin* was positively correlated with an increased *trunk sway*: individuals who had greater *trunk sway* during walking (those who were arguably more unstable, rotated their shoulders for larger relative spaces compared to their more stable counterparts) (Hackney & Cinelli, 2011). These results suggest that the natural M-L sway of walking is related to the ability to pass through an aperture and as the sway increases, as it does with instability, the possibilities for action also change. Franchak and colleagues (2012) support this hypothesis by observing that differences in the threshold between passable and impassable spaces are apparent when walking between obstacles compared to passing under barriers. The authors attribute the larger *spatial margin* needed for the horizontal openings to the greater spatial requirements created by the natural lateral sway compared to the vertical bounce associated with walking (Franchak et al., 2012). If this is indeed true, then passing through small spaces in environments where actions capabilities are challenged should result in modifications to normal aperture crossing behaviour. These studies all suggest that the possibilities for action consider both the size of the body and one's action capabilities or limitations.

The current study set out to further investigate the impact that action capabilities have on identifying possibilities for action, particularly with respect to how postural threat influences aperture crossing behaviour. To do this, an individual's ability to maintain balance was challenged by manipulating the level of postural threat while walking. This was achieved in two ways: (1) by reducing the width of the walking path and thereby reducing the size of the base of support (BOS); and (2) by elevating the narrow walking path to increase the risk associated with failing to maintain balance.

Manipulation of postural threat was chosen as the method of challenging balance control for two reasons. First, a number of studies have demonstrated that increasing postural threat by constraining or elevating the walking path is related to increases in anxiety associated with the potential consequences of falling, as evident by increased galvanic skin conductance (Ashcroft, Guimaraes, Wang, & Deakin, 1991; McKenzie & Brown, 2004; Naveteur & Roy, 1990). Second, research has demonstrated that static and dynamic balance control is altered when postural threat is increased (Adkin, Frank, Carpenter, & Peysar, 2000, 2002; Carpenter, Frank, & Silcher, 1999; Schrager, Kelly, Price, Ferrucci, & Shumway- Cook, 2008). When required to stand on an elevated platform, YA adopt a more cautious control strategy by leaning away from the edge of the platform and stiffening the control of posture (decreasing the amplitude and increasing frequency of postural sway) through increased co-activation of the muscles controlling the ankle joints (Adkin et al., 2000; Carpenter et al., 1999). During gait, narrow-based walking has been associated with increased M-L COM velocity and displacement suggesting that when the BOS is reduced, individuals have greater instability (Schrager et al., 2008). Furthermore, when walking on elevated surfaces, the increased postural threat results in adaptations to the gait pattern such as decreased velocity, shorter stride length and longer duration of time spent in double support, which all reflect a more cautious gait (Brown, Gage, Polych, Sleik, & Winder, 2002; McKenzie & Brown, 2004). Regardless of whether an individual is standing or walking, the aforementioned studies demonstrate that the alterations associated with the potential consequences of instability influence the manner in which balance and gait is controlled. Of the walking conditions tested in previous studies, walking on the elevated surfaces appear to pose the greatest threat to balance and results in the largest changes in gait.

Since aperture crossing research has suggested a correlation between instability and an increased *critical point* (Hackney & Cinelli, 2013a) and the postural threat literature demonstrates that increased postural threat (i.e., walking on an elevated surface) decreases stability during walking (Brown et al., 2002; McKenzie & Brown, 2004; Schrager et al., 2008), it was hypothesized that alterations to aperture crossing behaviour would be scaled according to the level of balance control. Specifically, individuals would employ a cautious approach to aperture crossing by reducing *walking speed* and continuing to rotate their shoulders for larger relative apertures when walking on both the narrow path and the elevated/narrow path, but the effects would be larger in the elevated/narrow path condition.

3.3 Methods

3.3.1 Participants

Twenty-nine healthy YA ($\bar{x}_{\text{age}}$ = 24.18 ± 3.2 years; 15 females and 14 males) volunteered to participate in the study (Table 3.1). Prior to the experiment, all participants completed a general screening questionnaire to confirm eligibility (Appendix B). Participants were included in the experiment if they were free of deficits or disorders that could affect postural control, locomotion and decision making; had no self-reported history of a hip, knee or ankle injury within the past six months, had normal or corrected-to-normal vision and could understand English instructions. Only participants who were comfortable standing on a chair to reach something off of a shelf above their head were included in the study. Participants who would not voluntarily stand on the chair or who reported that they would feel uncomfortable doing so, were excluded from the experiment.

All participants provided informed, written consent prior to the experiment. Ethical approval was obtained from the University of Waterloo’s Office of Research Ethics.

Table 3.1 – Participant characteristics by group assignment, including gender, age, SW and CP.

Group	Gender	Age (yrs)	SW (cm)	Normal CP	Experimental CP
Narrow Path	M	25	42.0	1.2	1.2
	F	30	46.0	1.3	1.3
	M	23	47.5	1.2	1.3
	M	25	49.0	1.3	1.3
	M	24	49.0	1.4	1.3
	F	21	41.5	1.4	1.4
	F	25	40.5	1.3	1.3
	M	24	47	1.2	1.2
	F	21	41.5	1.3	1.3
	M	26	52.0	1.3	1.3
	F	28	42.5	1.5	1.4
	Average/SD	***24.72±2.78***	***45.32±3.88***	***1.3±0.09***	***1.3±0.06***
Elevated/Narrow Path	F	22	44.0	1.3	1.4
	M	24	54.0	1.3	1.5
	M	26	45.5	1.2	1.5
	M	24	47.0	1.2	1.5
	M	30	45.0	1.3	1.5
	F	23	45.5	1.5	1.6
	F	22	40.5	1.3	1.5
	F	21	39.5	1.3	1.5
	M	21	51.0	1.3	1.4
	F	21	42.5	1.3	1.6
	F	25	40.0	1.2	1.5
	M	23	46.0	1.4	1.6
	F	22	43.0	1.3	1.2
	M	24	45.0	1.3	1.5
	M	20	47.0	1.2	1.5
	M	21	44.0	1.3	1.6
	F	25	40.5	1.3	1.5
	F	26	41.0	1.3	1.6
	Average/SD	***23.33±2.47***	***44.50±3.80***	***1.28±0.07***	***1.49±0.10***

3.3.2 Apparatus and Procedure

The experiment was conducted within a 7m (L) by 3m (W) area with two vertical pole obstacles (0.23m W by 2.4m H) located on both sides of the midline of the path, 5m from the starting position (Figure 3.1). The position of the two obstacles created a space for participants to walk through, which could be adjusted to various sizes relative to each participant's shoulder width. For all trials, participants were instructed to walk to the end of the path and pass between the poles without colliding with them. Participants were also encouraged to rotate their shoulders while passing through the obstacles if they perceived that the opening was too small to walk straight through without adjusting their body position. Avoiding the aperture all together by walking to the left or the right of the obstacles was not permitted. Between experimental trials, participants faced away from the path while the researchers manually adjusted the position of the obstacles.

Kinematic data was measured using the OptoTrak camera system (Northern Digital Inc., Waterloo, ON, Canada) at a sampling frequency of 60Hz. The IRED marker set-up was the same as that outlined in Chapter 2 (Appendix C).

3.3.3 Experimental Design

Aperture crossing studies often normalize the width of the aperture to the size of the participant's shoulders and report the group behaviours that emerge. Although this approach takes into consideration various body sizes, these studies assume that all individuals have similar action capabilities and neglect the possibility that abilities can also vary across individuals of the same body size. This is especially important in environments where action capabilities are challenged, as a particular challenge may affect individuals differently. By accounting for individual differences, an experiment can better identify whether manipulating one's action capabilities effects aperture crossing behaviour. Therefore the current study normalized the set of aperture widths to an individual's shoulder width as well as their performance behaviour in a baseline condition.

To normalize the experiment to an individual's performance, participants first completed a block of baseline trials to identify their individual *critical point* during normal, ground-level walking. To do so, participants walked along the path towards an end-goal at a self-selected pace and passed through an aperture 5m from the start. The aperture ranged from 1.1 to 1.5x SW in increments in 0.1. Each aperture width was presented five times in randomized order, for a total of twenty-five trials. On every trial, two experimenters independently recorded whether the participants visibly rotated their shoulders to pass through the aperture. Upon completion of the baseline trials, the experimenters identified the largest aperture width in which a shoulder rotation was produced for at least three of the five trials (i.e., 60% of trials). This value was identified as the participant's ‘‘normal’’ *critical point* and was used to normalize the subsequent experimental trials to each individual. Note that the raters were only used to identify the observable shoulder rotations at the experiment was being conducted for the purpose of individualizing the experimental trials. These observations were not used during data analysis.

Following the baseline trials, participants were randomly assigned to one of two groups: (1) the narrow path group, where participants walked along a 7m (L) by 0.2m (W) path at ground level; or (2) the elevated/narrow path group, where participants walked along a path that was 7m (L) by 0.2m (W) and raised 0.4m off the ground (Figure 3.1). All participants received the same instructions for the experimental trials as they did for the baseline trials but were also encouraged to avoid stepping off and/or falling off the path. Two spotters walked on either side of the path during the trials in order to provide support for the participant if a trip, a fall or a loss of balance occurred. Trips and falls were not anticipated for the narrow path group since the path was located at ground level, however the spotters were used for the purpose of maintaining consistency between conditions. For both groups, the aperture width for the first five experimental trials was set to each participant's *critical point* identified from the baseline trials. This was done to directly compare whether the narrow path and/or the elevated/narrow path affected the individual's aperture crossing behaviour at the aperture width corresponding to the ‘‘normal’’ *critical point*. The researchers recorded whether the participant rotated his or her shoulders when passing through the aperture in order to determine the range of aperture sizes to be presented in the final fifteen experimental trials. If the participant rotated their shoulders for at least three out of the five trials (i.e., 60% of the trials), the following fifteen trials were randomly presented at 0.1, 0.2 and 0.3 increments larger than the *critical point* value (five trials of each). Rotating the shoulders at least three of the five trials suggest that the participant either: (1) maintained the same *critical point* as baseline; or (2) that their *critical point* value had increased. Similarly, if the frequency of shoulder rotations for the first five experimental trials was less than three, participants received fifteen randomly presented aperture widths that were 0.1, 0.2 and 0.3 increments smaller than their baseline *critical point*s. Rotating the shoulders less than three trials suggests that the *critical point* decreased. Therefore, providing apertures smaller than the ‘‘normal’’ *critical point* value would allow for the new *critical point* to be identified for the challenged walking condition.

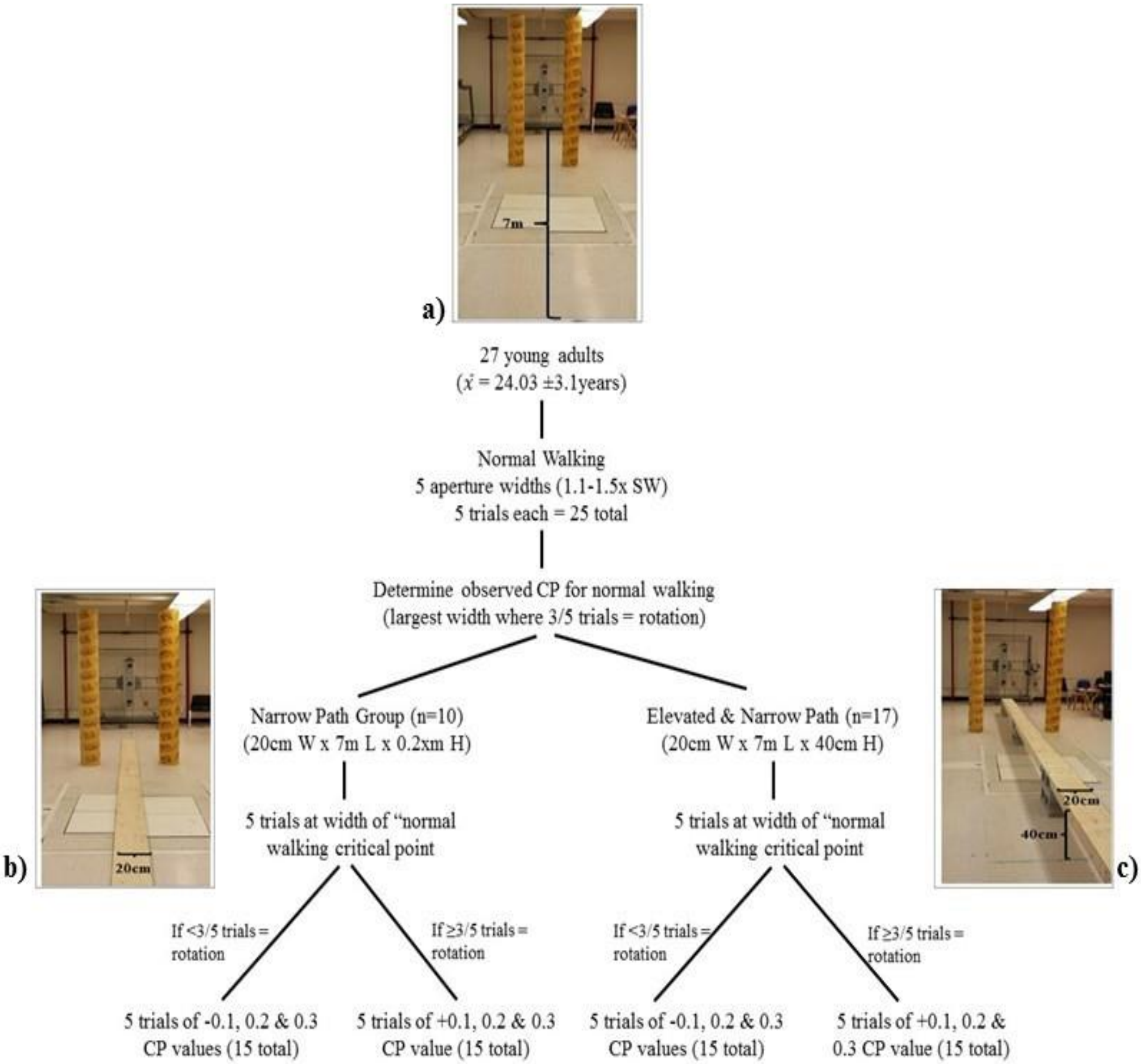

Figure 3.1 – Experimental set-up and methods for the three testing conditions including, **a)** normal, ground-level walking, **b)** narrow ground-level walking and **c)** elevated/narrow walking.

3.3.4 Data Analysis

For the purpose of this study, an individual's *critical point* was defined as the largest aperture width that was considered impassable. Since participants were instructed to walk on a narrow or an elevated/narrow path through the aperture, impassable apertures were considered those where the participant rotated his or her shoulders. Unlike Chapter 2, participants were not permitted to walk around the aperture (because they were restricted to walking on the narrow or elevated/narrow path) and therefore, only shoulder rotations were considered changes in action at TOC. For group *critical point*s, the largest aperture width at which the *magnitude of rotation* (described in Chapter 2, Section 2.3.5) was significantly different than straight walking was considered the *critical point*. When determining an individual's *critical point,* the largest aperture width at which a shoulder rotation occurred at least three of the five trials (60%) was recorded. Individual data was used to identify the percentage of participants who changed (or did not change) their *critical point* between conditions.

In addition to the *critical point*, other variables of interest included: *approach velocity*, *velocity at TOC, trunk sway,* and *spatial margin*. These calculations are described in Chapter 2 (Section 2.3.5). Additionally, the *onset of rotations* and the *onset of changes in velocity* were also calculated. If the *velocity at TOC* fell outside three standard deviations of the average walking speed during the approach phase, a significant change in velocity was identified and the distance from the aperture (using the A–P COM) in which this change was first initiated was reported. A similar method was used to determine the *onset of rotation* for trials where participants rotated their shoulders. Appendix A provides a visual representation of the dependent variables used in this study.

3.3.5 Statistical Analysis

The *magnitude of rotation* at TOC were compared across aperture widths to identify the *critical point* for each condition using a 2 (walking condition) x 2 (group) x 6 (aperture width) GLM with repeated measures. The largest aperture at which the *magnitude of rotation* was significantly different than zero was identified as the *critical point* using a Tukey's HSD post hoc analysis.

In order to determine if manipulation of postural threat influenced other aperture crossing behaviours, all other variables were compared between the aperture width that corresponded to the individual's *critical point* in the baseline trials to the same aperture width in the experimental trials (i.e., the first five experimental trials). All variables were analyzed using a 2 (walking condition; baseline vs. experimental trials) x 2 (group; narrow vs. elevated/narrow) GLM with repeated measures and *p*-values less than 0.05 were considered significant.

To confirm that any differences in behaviour were due to the manipulation of postural threat and not because the two groups differed from one another initially, all dependent variables were compared between groups in the baseline condition. A series of 5 (aperture width; 1.1–1.5) x 2 (group; narrow vs. elevated/narrow) GLM with repeated measures were run for this analysis and *p*-values less than 0.05 were considered significant.

3.4 Results

A 2 (walking condition) x 2 (gender) x 5 (aperture width) GLM examined whether the *magnitude of rotation* differed across these factors. Results revealed a significant effect of aperture width ($F_{(1, 26)} = 10.39$, $p < 0.01$, $ŋ^2 = 0.71$), where the *magnitude of rotation* decreased as the size of the aperture increased and a significant effect of walking condition ($F_{(1, 62)} = 4.32$, $p < 0.05$, $ŋ^2 = 0.42$). For both the baseline walking trials and the narrow path group, post hoc analysis identified that aperture width 1.3 was the largest width where the *magnitude of rotation* was significantly different than zero while the elevated/narrow path group's was 1.5 ($p < 0.05$ for all walking conditions; Figure 3.2a).

After determining the individual *critical point*s for all experimental trials, a 2 (walking condition) x 2 (group) GLM was conducted to confirm the value of the *critical point* for the group. Results revealed a significant interaction between walking condition (baseline vs. experimental trials) and group (narrow path vs. elevated/narrow path) ($F_{(1, 26)} = 28.732$, $p < 0.05$, $ŋ^2 = 0.60$), where only participants in the elevated/narrow path group had a larger *critical point* value in the experimental trials compared to the baseline trials. Specifically, in the baseline walking trials, both groups had an average *critical point* of 1.3 (±0.02). In the experimental trials, the narrow path group maintained a similar *critical point* to that of baseline ($\bar{x} = 1.21 \pm 0.03$) whereas the individuals in the elevated/narrow path group had an average *critical point* of 1.5 (±0.02). Furthermore, individual analysis revealed that 83% of the participants in the elevated/narrow path group increased their *critical point* in the experimental trials compared to the baseline trials, while this increase was only observed for 18% of the participants in the narrow path group (Figure 3.2b). Individual *critical point* values for are reported in Table 3.1.

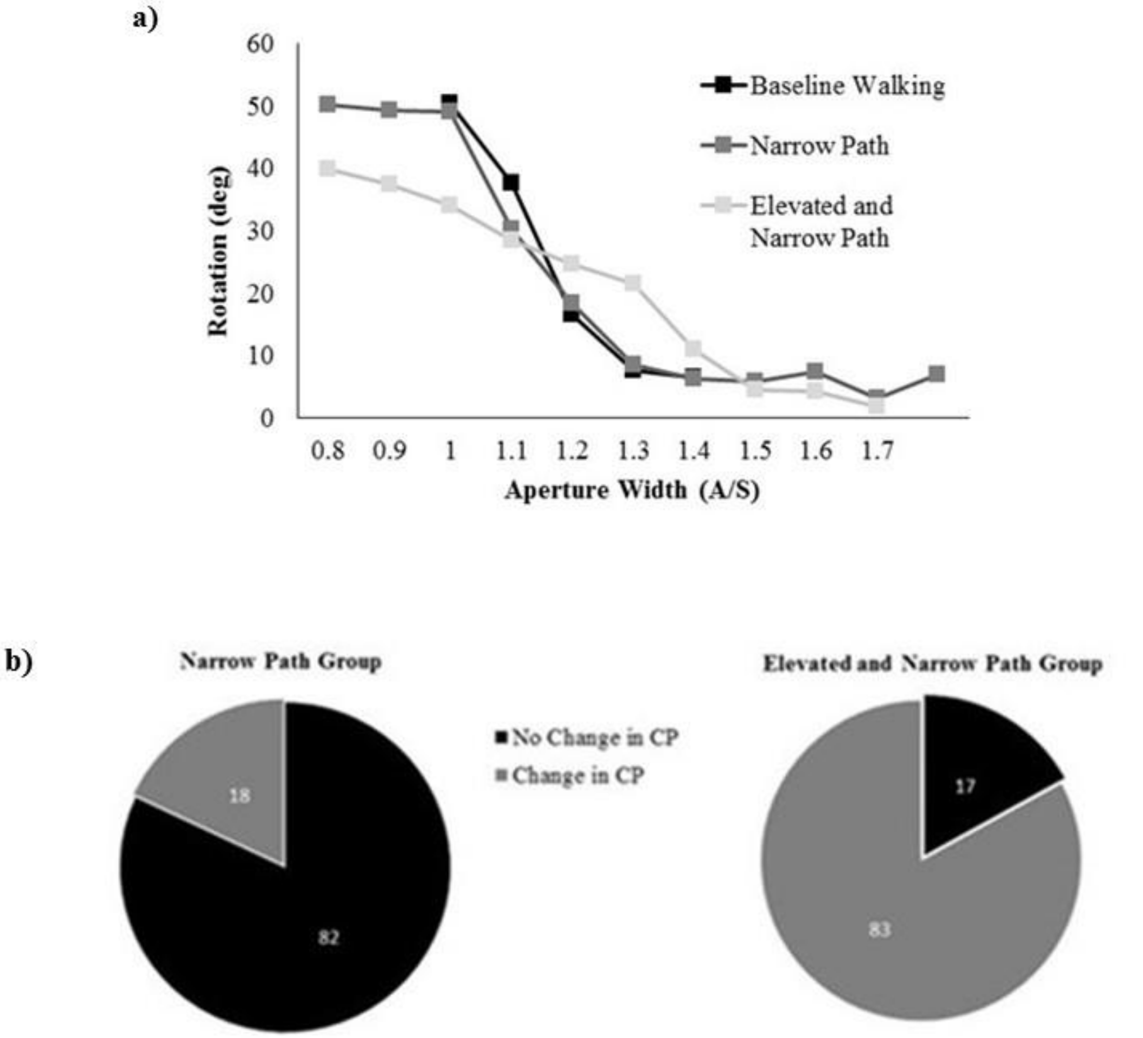

Figure 3.2 – a) The *magnitude of rotation* for each condition. Rotations decreased as aperture size increased (p<0.01) but rotations continued at larger apertures for the elevated/narrow group (p<0.05), and **b)** the percentage of individuals who changed their CP in the experimental trials. 83% of participants increased their CP when walking on the elevated/narrow path, while only 18% did so for the narrow path.

A 2 (walking condition) x 2 (group) GLM with repeated measures was conducted to determine whether all other dependent variables were influenced by postural threat in a similar manner as shoulder rotations at the value of the *critical point* (Table 3.2). Results revealed a significant effect of walking condition for *magnitude of rotation* (F $_{(1, 26)}$ = 37.69, $p < 0.001$, ŋ^2 = 0.72), *approach velocity* (F $_{(1,26)}$ = 57.77, $p < 0.001$, ŋ^2 = 0.35), *trunk sway* (F $_{(1, 26)}$ = 16.29, $p < 0.001$, ŋ^2 = 0.42), *velocity at TOC* (F $_{(1, 26)}$ = 16.86, $p < 0.001$, ŋ^2 = 0.41) and *spatial margin (*F $_{(1, 26)}$ = 15.26, $p<0.01$, ŋ^2 = 0.30), where the *magnitude of rotation*, *approach velocity* and the *velocity at TOC* decreased and *spatial margin* and *trunk sway* increased at the *critical point* during the experimental trials (constrained path, increased threat) compared to baseline (normal walking). Furthermore, a significant interaction was identified between group and walking condition for *magnitude of rotation* (F $_{(1, 26)}$ = 17.71, $p < 0.001$, ŋ^2 = 0.217), *approach velocity* (F $_{(1, 26)}$ = 11.22, $p < 0.01$, ŋ^2 = 0.26), *trunk sway* (F $_{(1, 26)}$ = 9.52, $p < 0.05$, ŋ^2 = 0.28), *velocity at TOC* (F $_{(1, 26)}$ = 8.821, $p < 0.05$, ŋ^2 = 0.34) and *spatial margin* (F $_{(1, 26)}$ = 7.59, $p< 0.05$, ŋ^2 = 0.25), where individuals in the elevated/narrow path group significantly decreased their *approach velocity* (Figure 3.3a), *velocity at TOC* and *magnitude of rotation*, and increased their *trunk sway* (Figure 3.3b) and *spatial margin* in the experimental trials compared to the narrow path group ($p < 0.05$ for all comparisons). The two groups did not differ from one another in the baseline trials for any of the dependent variables, suggesting that the differences observed during the experimental trials were not due to the two groups differing from one another to begin with.

Table 3.2 – Mean and standard deviation results for all conditions. Variables included the CP, *magnitude of rotation*, *approach velocity*, *velocity at TOC* and *trunk sway*.

Dependent Variables	**Narrow group**		**Elevated/Narrow group**	
	Baseline	**Experimental**	**Baseline**	**Experimental**
Critical point	1.3 ±0.02	1.3 ±0.5	1.31 ±0.03	1.5 ±0.07
Magnitude of rotation (deg)	38.98 ± 4.13	35.17 ±8.59	41.03 ±5.43	20.92 ±4.14
Approach velocity (m/s)	1.42 ±0.07	1.31 ±0.07	1.43 ±0.06	1.18 ±0.09
Velocity at TOC (m/s)	1.40 ±0.08	1.32 ±0.06	1.41 ±0.07	1.20 ±0.08
Trunk sway (deg)	3.01 ±0.02	4.09 ±0.03	3.21 ±0.03	6.22 ±0.04
Spatial margin (cm)	8.21 ±1.39	9.01 ±1.68	8.03 ±2.02	13.15 ±3.19

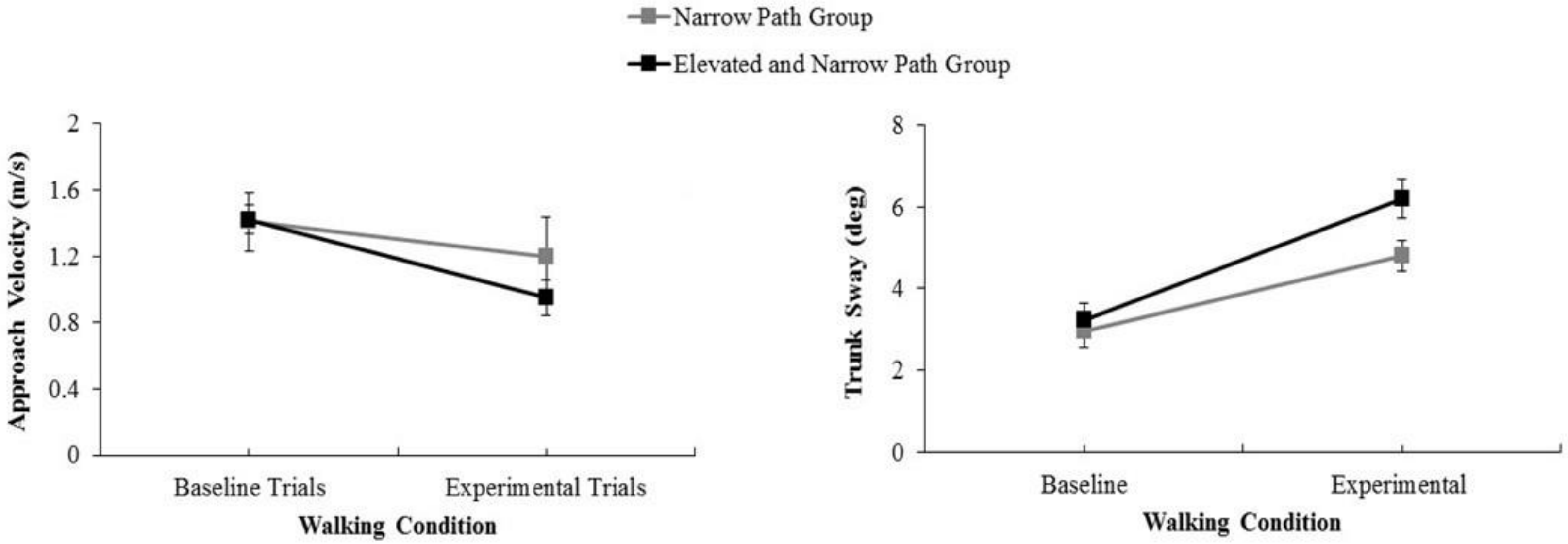

Figure 3.3 – a) *Approach velocity* and, **b)** *trunk sway* for this baseline and experimental trials. Both groups walked slower and increased their sway in the experimental trials compared to baseline ($p<0.001$) but individuals in the elevated/narrow path group significantly reduced their walking speed and increased their sway compared to the narrow path group ($p<0.01$ and $p<0.05$ respectively).

3.5 Discussion

The current study set out to further investigate the impact that action capabilities have on aperture crossing behaviour, particularly with respect to how postural threat influences the division between passable and impassable apertures. When determining the possibility for actions, both an individual's body size and action capabilities are thought to contribute to the performance of a desired action (Comalli, Franchak, Char, & Adolph, 2013; Fajen & Matthis, 2011; Fajen, Riley, & Turvey, 2009; Warren & Whang, 1987). In the current study, action capabilities were altered by manipulating postural threat and increasing the consequence associated with instability. As with previous research (Hackney et al., 2013; Hackney & Cinelli, 2013b; Warren & Whang, 1987; Wilmut & Barnett, 2010), the aperture widths in the current study were normalized to each individual's shoulder width in order to account for variations in body size. However, the current study also considered an individual's aperture crossing performance to account for differences in action capabilities. In the baseline trials, participants completed the aperture crossing task for normal, ground-level walking in order to identify their ‘‘normal’’ *critical point*. This relative aperture width was then presented for five consecutive trials while walking on either the narrow path or elevated/narrow path, depending on the participant's assigned group. Each individual's *magnitude of rotation* in these subsequent trials was compared to that of the baseline trials in order to determine the specific aperture widths to be presented in the remaining experimental trials. By doing so, this study directly considered both the size of the body and the individual's aperture crossing performance behaviour when determining whether the manipulation of such abilities influenced aperture crossing behaviour.

Similar to previous studies (Adkin et al., 2000, 2002; Brown et al., 2002; McKenzie & Brown, 2004), postural threat was altered by increasing the height of the walking path. Analysis of *walking speed* and *trunk sway* confirmed that the manipulation of postural threat had the desired effect. Participants walked slower (Figure 3.3a) and demonstrated an increased *trunk sway* (Figure 3.3b) when walking on both the narrow path and the elevated/narrow path, however the effect was more pronounced in the elevated/narrow path condition. As with previous research, these results support the observation that increasing postural threat elicits a more cautious walking behaviour (Brown et al., 2002; Carpenter et al., 1999; McKenzie & Brown, 2004).

The results of the current study provide additional support for the argument that increased postural threat leads to cautious behaviour when passing through apertures, as it not only affected gait characteristics but also influenced the size of the *critical point*. Individuals rotated their shoulders more often at larger relative apertures (i.e., had a larger *critical point*) when on an elevated/narrow surface compared to both baseline walking and narrow path walking. This larger *critical point* has been argued to be indicative of a cautious approach to aperture crossing (Comalli et al., 2013; Hackney & Cinelli, 2011, 2013a), as individuals require larger relative aperture widths to pass through before modifying body configuration. In line with these findings, Comalli et al. (2013) demonstrated that individuals made more conservative decisions about passing through apertures when the penalty for error was falling off a ledge compared to when the risk of falling was not present. Additionally, research examining stepping behaviours when stepping over obstacles also demonstrates larger *spatial margin*s under conditions of instability (McKenzie & Brown, 2004; Pijnappels, Bobbert, & van Dieen, 2001). Furthermore, McKenzie and Brown (2004) examined how individuals negotiate obstacles while walking at four different levels of postural threat: an unconstrained/ground-level path, a constrained/ground-level path (0.15 m wide), an unconstrained/elevated path (0.6 m high) and a constrained/elevated path (0.15 m wide and 0.6 m high). In their analysis it was observed that when stepping over an obstacle on the walking path, participants altered their toe clearance to the level of postural threat, such that the space between the toe and the obstacle was greatest when on the constrained/elevated path. Similarly, Pijnappels et al. (2001) demonstrated that when participants receive a warning about a potential tripping hazard in advance of a walking trial, individuals increase their minimal toe clearance by 51.6% compared to walking without the forewarning. The above-mentioned findings in combination with the results from the current study suggest that when stability is challenged during walking, individuals employ a cautious behaviour by reducing *walking speed*, increasing toe clearance, or continuing to rotate the shoulders for larger relative apertures widths to reduce the chance of collision.

This cautious behaviour observed during the elevated/narrow conditions was further demonstrated when assessing *magnitude of rotation*s at TOC. The results demonstrate that for a given aperture width that produced shoulder rotations during the flat ground walking produced lower magnitudes of rotation during the platform conditions (Figure 3.2). Rotating the shoulders changes the rate at which the COM moves towards the BOS. Larger rotations would therefore increase the chance of experiencing instability. By rotating the shoulders a smaller amount on the elevated surface, individuals reduce the chance of instability and helped maintain the forward trajectory of their COM. This strategy has been previously observed in an OA population where OA walking on ground level will rotate their shoulders more often (at larger aperture widths) but the magnitude of the rotations was much smaller (Hackney & Cinelli, 2011). Therefore it is possible that, YA walking on an elevated/narrow surface attempted to control the direction of locomotion and reduce the chance of instability in a similar manner observed at ground level in an OA population.

In addition to being more cautious, the larger *critical point* in the elevated/narrow pathways (but not the narrow pathways) may also be attributed to an increased *trunk sway*. Previous work in our lab (Hackney & Cinelli, 2013a) demonstrated a positive relationship between *trunk sway* and the *critical point*, which we suggested as an explanation for why OA maintained a larger *critical point* compared to their younger counterparts under normal walking conditions (Hackney & Cinelli, 2013a). In this study, it was proposed that individuals are aware of and will adjust their actions to accommodate for changes in both the physical size of their shoulders and the variability of the M-L *trunk sway* (i.e., they account for differences in their action capabilities). Similarly, research has demonstrated that individuals maintain a greater *spatial margin* when walking through horizontal openings than they do for vertical openings (Franchak et al., 2012). It was argued that these differences were likely linked to the fact that individuals swayed more in the M-L direction (applicable to the walking through narrow openings) than that in which they bounced in the vertical direction (applicable to walking under barriers) (Franchak et al., 2012). At first glance, the results of the current study appear to support such a hypothesis since *trunk sway* increased as a function of postural threat. However, a Pearson's correlation comparing *trunk sway* and *critical point* (collapsed across walking conditions) revealed no significant relationship between the two variables. This insignificant result is likely driven by the fact that the narrow path group's *critical point* did not change relative to baseline.

Although previous research suggests that the magnitude of this effect changes as a function of postural threat, the current study only observed a larger *critical point* when the participants were in the situation that posed the greatest consequence to instability (i.e., the elevated/narrow path group). On average, the *critical point* increased from 1.3 for baseline walking trials to 1.5 when walking on an elevated path (following the *critical point* definition used in this study). Meanwhile, individuals in the narrow path group maintained the same *critical point* of 1.3 from the baseline trials to the experimental trials. Since gait characteristics were significantly altered in the narrow path condition compared to baseline but the *critical point* was not, it is possible that the narrow path did not impose enough postural threat to elicit changes in how often an individual rotates his or her shoulders.

An alternative explanation for why a larger *critical point* was observed for the elevated/narrow path but not for the narrow path may be explained by the change in eye height associated with the increased elevation. Warren and Whang (1987) suggested that eye height can influence perception of action capabilities. When standing on a false floor that was raised 0.26 m off the ground, judgements as to whether an individual could pass through an aperture without rotating the shoulders differed than when standing at ground level. Furthermore, Mark (1987) demonstrated that when individuals walked while wearing 10cm blocks strapped to their feet, the judgements about the climbability of stairs and the sitability of chairs was altered. Recently, Fajen (2013) postulated that the knowledge of the relation between one's body size and eye height is a constant ratio that is used in identifying possibilities for action. In the event that either eye height or body size is altered, the perceptual-motor system must recalibrate itself to accommodate for the change in the relationship. Walking on an elevated surface changes the eye height, but not the width of the body which could alter the relationship between the body and the environment. In the aperture crossing environment, this change in eye height may explain the increase in *critical point* observed in the elevated path but not the narrow path (since the ratio was not affected). However, in order to test this hypothesis future work should assess whether *critical point*s change when eye height is altered but stability is not.

3.6 Conclusions

Gibson (1979) proposed that humans guide behaviours by perceiving what environmental objects offer or afford for action. Affordances are defined as the functional utility of an object for an individual based on the fit between body size and object size (Warren, 1984). Overall, the results of the current study provide evidence for the argument that action capabilities play an important role in determining affordances by identifying the contribution that dynamic stability has on the passability of apertures. Dynamic stability likely infers action capabilities through changes in visual information. If an observer’s level of stability is similar during both static and dynamic situations (i.e., they are very stable), the change in visual information (optic flow) when the observer begins to move is predictable and consistent with that of the stable environment. However, if the observer’s level of stability is different between static and dynamic situations (i.e., the observer is unstable during locomotion), there is a mismatch between the predicted change and the actual change in visual information which may result in different behaviour. In the current study, the consequences of instability associated with walking on an elevated/narrow path influenced the passability of apertures such that individuals required a larger space between their shoulders and the obstacles at TOC. The elevated/narrow path likely induced a change in behaviour as a result of a mismatch between the predicted and actual changes in visual information.

Similar effects have been observed in an OA population, who are more unstable during flat ground walking than their younger counterparts and who require a larger *critical point* when passing through apertures (Hackney & Cinelli, 2011). This idea is further emphasized by the fact that in the current study, the *critical point* for the narrow path walking was unchanged. Dynamic stability in this condition was likely not different enough from normal ground walking to induce large differences in visual information available for determining action capabilities. Therefore the results of the current study support the idea that affordances can be guided by an observer's action capabilities and that during locomotion, one's level of stability influences aperture crossing behaviour.

- Chapter 4 -

DOES THE PASSABILITY OF APERTURES CHANGE WHEN WALKING THROUGH HUMAN VERSUS POLE OBSTACLES?

Adapted from:

Hackney, A. L., Cinelli, M. E., & Frank, J. S. (2015). Does the passability of apertures change when walking through human versus pole obstacles? *Acta Psychologica*, *162*, 62 – 68.

4.1 Abstract

The current study set out to evaluate how individuals walk through apertures created by different stationary obstacles. Specifically, we examined whether the passability of apertures differed between human and pole obstacles by quantifying aperture crossing behaviours such as the *critical point*. Participants walked a 7m path toward a visible goal located at the end. A narrow space was presented 5 m from the starting location and participants were instructed to walk through the aperture without colliding with the obstacles. Throughout the experiment the aperture was either created by two pole obstacles or two human confederates. On any given trial, the distance between the poles or the human obstacles ranged between 1.0 and 1.8x SW. Results revealed that, when the obstacles were humans, individuals have an increased *frequency* and *magnitude of shoulder rotations*, a larger *critical point* (1.7 vs 1.3 for poles), initiated a rotation earlier, maintained a larger *spatial margin* and had a slower *walking speed* compared to the pole obstacles. Furthermore, correlational analyses revealed that the amount of change between an individual's *critical point* for the poles and the *critical point* for the human obstacles was related to social risk-taking and changes in *walking speed*. Therefore, it appears that the passability of apertures changes when walking between two people versus two objects such that more space and greater caution are needed for human obstacles. It is possible that the greater caution observed for human obstacles is needed in order to account for the personal space requirements of others that does not exist in the same extent for pole obstacles. Furthermore, the degree of caution used when walking between two humans may be related to social factors and/or how comfortable an individual is in a social situation.

4.2 Introduction

When confronted with a narrow space while walking, many studies have observed that the *magnitude* and *frequency of shoulder rotations* produced at the TOC increases as the size of the aperture decreases (Franchak et al., 2012; Hackney, et al., 2013; Warren & Whang, 1987; Wilmut & Barnett, 2010). In situations where the individual aims to avoid making any contact with the aperture, Warren and Whang (1987) identified that significant shoulder rotations occur for apertures 1.3x SW and smaller but are not required for apertures larger than this value. This division between spaces that elicit a shoulder rotation and spaces that do not is referred to as the *critical point* for aperture crossing (Warren & Whang, 1987). More recently, similar behaviours have been observed during unconfined aperture crossing tasks, where participants were permitted to either walk around the aperture or walk through with or without rotating the shoulders (Hackney et al., 2013). When faced with two pole obstacles that create an aperture along the travel path, participants also chose to walk through apertures larger than 1.3x SW but avoided spaces smaller than this value by walking to the outside of the poles. Furthermore, this consistent *critical point* has been observed when running through apertures (Hackney, Zakoor & Cinelli, 2015), while carrying wide objects (Hackney et al., 2014) and with a decreased BOS as a result of a narrow walking surface (Hackney, Cinelli, Denomme & Frank, 2015). These studies suggest that the affordance of aperture crossing is 30% larger than the width of the shoulders, that individuals will scale the magnitude of their shoulder rotations to maintain this *spatial margin* and that this value is quite consistent.

The fact that individuals act to maintain a *spatial margin* between their bodies and the aperture is not surprising, since the obstacle circumvention literature also demonstrates a desire to maintain a *spatial margin* for walking around single obstacles. When avoiding a single stationary or a single moving obstacle, individuals maintain a consistent and elliptic-shaped protective zone between the body and the obstacle at the TOC (Gerin-Lajoie, Richards & McFadyen, 2005). The role of this *spatial margin* is thought to provide a margin large enough to ensure sufficient time to perceive upcoming hazards and perform adjustments to gait in order to successfully avoid colliding with the obstacles. Research has also identified specific variables that can be used to describe when adjustments to path trajectory will be made when approaching an obstacle (i.e., the A-P *spatial margin*). Cinelli and Patla (2007) described how time-to-contact (TTC) is used to determine when a change in the travel path trajectory is required when avoiding an oncoming obstacle. Meanwhile, Olivier and colleagues (2012) reported that the minimal predicted distance (MPD) can be used to predict when two walkers will make a locomotor adjustment to avoid one another. Cinelli and Patla (2007) also identified that individuals will deviate further from the straight path trajectory in order to maintain a M-L *spatial margin* at the TOC. The idea of a protective zone for obstacle circumvention can also be used to describe the avoidance behaviours used during aperture crossing. Individuals rotate their shoulders for spaces that are up to 1.3x SW during aperture crossing, which suggests that they also act to maintain a protective zone when passing through without collision. Specifically, the maintenance of an elliptic-shape *spatial margin* of 0.3m in the M-L direction and 2.4m in the A-P direction is maintained has been described for aperture crossing (Hackney & Cinelli, 2013b). To date, aperture crossing studies examine spaces that are created by objects such as lightweight poles, panels, and doorways. Although it is important to understand how individuals navigate through apertures of such materials, cluttered environments also consist of small spaces created by other people such as when walking in a busy mall or moving through a crowded party. The question remains as to whether individuals pass through spaces created by other people in the same manner that they would pass through pole obstacles. In other words, is the passability of apertures similar when walking through people as it is with poles? Do individuals maintain a similar *spatial margin* and *critical point* for other people as they do for pole obstacles?

Although research has yet to consider the idea of the *critical point* for human environments, studies have examined how individuals circumvent other individuals on the locomotor path. Knowles and colleagues (1976) investigated the differences in spatial boundaries created by other people and environmental objects by observing how individuals pass by an empty bench, on person, a group of two and a group of three people. The results demonstrated that individuals walked closer to an empty bench compared to a person, farther from a group than a single individual and further from large groups compared to small groups. The authors suggested that the larger deviations in path trajectory (i.e., maintaining a larger boundary) may have been implemented to account for the intentions of others and their possibilities for future movement. This is in line with recent work investigating the ability to judge the affordances of others. Creem-Regehr and colleagues (2013) demonstrated that observers are able to account for both the physical size of their own body and that of another person when asked to judge whether an aperture was passable while walking beside that person. Furthermore, Chang and colleagues (2009) measured the minimal passable width for an adult and a child walking side-by-side through an aperture, while Davis (2009) examined the passage threshold for two adults walking side-by-side. In both cases, the results revealed that the minimal aperture widths that individuals could pass through were scaled to include the shoulder width of both walkers, suggesting that people perceived the passability of apertures in references to themselves and others. The above-mentioned studies suggest that the larger *spatial margin* maintained when walking around another person on the travel path may be related to the fact that individuals account for the affordance of others (such as the amount of space the other person requires) when modifying their own actions. Therefore, it is hypothesized that individuals will maintain a larger *critical point* when passing through two human obstacles compared to two pole obstacles simply because they are accounting for the social factors involved with invading another individual's personal space.

4.3 Methods

4.3.1 Participants

Nineteen healthy YA ($\bar{x}_{\text{age}}$ = 24.65 ± 4.49 years; 9 females and 10 males) volunteered to participate in the study (Table 4.1). Prior to the experiment, all participants completed a health screening questionnaire in order to determine eligibility. Similar to previous studies reported in this thesis, participants were included in the study if they were free of deficits or disorders affecting their balance and locomotion; had no hip, knee or ankle injuries within the last two years, and had normal or corrected-to-normal vision. Ethics approval was obtained from the University of Waterloo's Office of Research Ethics.

Table 4.1 – Participant characteristics including gender, age, SW, height and CP for both the pole and human obstacles.

Participant	**Gender**	**Age**	**SW**	**Height**	**CP (Poles)**	**CP (Human)**
1	F	22	37.5	173	1.4	1.7
2	F	21	42	164	1.3	1.6
3	F	23	44	161	1.2	1.5
4	F	28	43	164	1.3	1.6
5	F	23	44	179	1.3	1.4
6	F	19	42	161	1.3	1.6
7	F	29	45	170	1.4	1.7
8	F	21	42	164	1.2	1.6
9	F	26	40	167	1.2	1.5
10	M	21	50	179	1.1	1.7
11	M	21	48	188	1.1	1.5
12	M	26	53	188	1.2	1.5
13	M	30	49	188	1.2	1.7
14	M	28	54	185	1.3	1.7
15	M	25	50	185	1.4	1.8
16	M	30	51	176	1.3	1.6
17	M	25	46	182	1.2	1.6
18	M	20	47	182	1.2	1.6
19	M	20	45	192	1.3	1.8
Average/SD	**---------**	***24.6±4.49***	***45.7±4.39***	***175.5±10.54***	***1.26±0.09***	***1.61±0.11***

After participants provided their informed, written consent, the experimenters recorded the shoulder width and height of each participant using a measuring tape (Table 4.1), and participants also completed a risk-taking questionnaire. The domain-specific risk-taking scale for adult populations (DOSPERT) is a psychometric scale that assesses risk taking in five domains: financial, health, recreational, ethical and social (Blais & Weber, 2006). The questionnaire requires participants to rate the likelihood that they would engage in certain risky activities. For the purpose of the current study, the social domain component of the scale was considered (Appendix D).

4.3.2 Apparatus and Procedure

The experiment was conducted on an 8m long path with a visible goal located at the end. Two obstacles were positioned 5m from the starting location on either side of the midline. On half the trials, the obstacles consisted of two vertical poles (0.23m W x 2.4m H) (Figure 4.1a) whereas the obstacles for the other half of the trials consisted of two people (i.e., confederates) (Figure 4.1b). For consistency purposes, both of the confederates were female and had similar shoulder widths. In order to reduce social cues, the confederates wore sunglasses and maintained a neutral facial expression throughout the experiment. The same confederates were used throughout the entire study. The space between both types of obstacles ranged between 1.0 and 1.8x SW (in increments of 0.1) on any given trial. For the pole obstacles this width was measured from the inner edge of both poles, while the space between the confederates was measured between the inner edges of each confederate’s shoulders (i.e., the smallest distance between them). To ensure the smallest distance between the confederates remained at the shoulders, the confederates always stood with their hands firmly pressed against their sides and wore a tight-fitted shirt to avoid baggy sleeves reducing the distance.

Participants completed two counter-balanced blocks of trials based on obstacle type (poles and confederates). It is important to note that although we wanted to reduce the effects of social cues such as eye contact and various facial expressions, we also wanted to ensure that participants remembered the human obstacles did have human qualities. To do this, we incorporated five catch trials randomly throughout the experiment where the human obstacles would begin walking forward when the participant reached a mark on the ground (2m from the aperture). These catch trials were not analyzed and were included merely to ensure the human obstacles portrayed some human-like qualities, such as the ability to move.

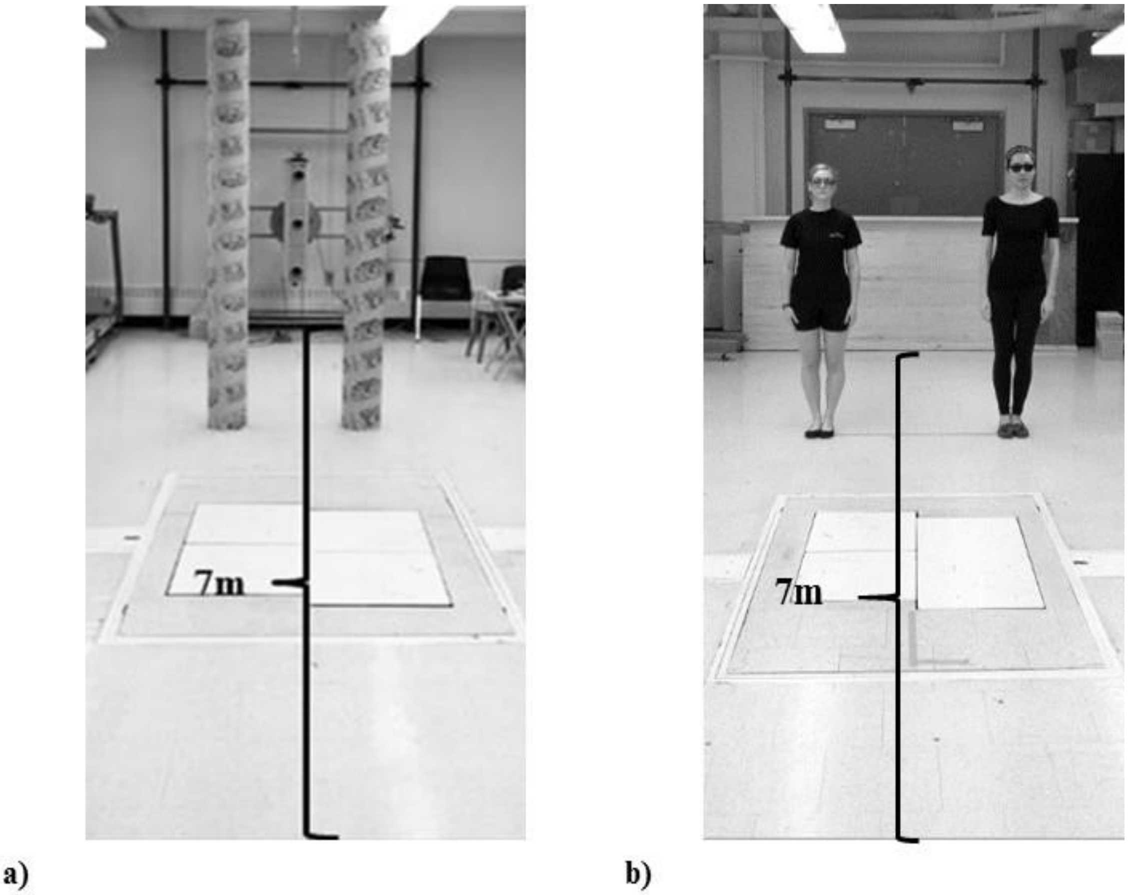

Figure 4.1 - Experimental set up for **a)** the pole obstacles and **b)** the human obstacles.

On all trials, participants were instructed to walk at a natural pace toward the goal and avoid colliding with the two obstacles. Participants were instructed to walk between the obstacles on every trial and were told that they could rotate their shoulders if they felt it was necessary for avoiding a collision with the obstacles. Prior to the start of each trial the participants turned away from the aperture while the experimenters manually adjusted the position of the pole obstacles or the confederates moved to the appropriate marking on the ground.

Kinematic data was measured using the OptoTrak camera system (Northern Digital Inc., Waterloo ON CA) at a sampling frequency of 60Hz. The marker set-up was the same as reported in studies one and two (Appendix C).

4.3.3 Data Analysis

Since the purpose of this study was to identify how the action strategies used for walking through two people differs from walking through two pole obstacles, general aperture crossing behaviours were compared between the two conditions. In line with the analysis described in this document, the variables of interest in the current study included the *magnitude of rotation, critical point, onset of rotation, approach velocity, velocity at TOC* and *spatial margin.* A detailed description of how these variables were calculated is included in Chapter 2 and 3 and Appendix A provides a visual representation of these variables.

For the purpose of the study, the *critical point* was defined as the largest aperture width at which participants changed their body orientation in order to pass through the narrow space without a collision occurring. The group *critical point*s were determined by statistically identifying the largest aperture width where the *magnitude of rotation* was significantly different than normal walking. Individual *critical points* were identified as the largest aperture width at which a shoulder rotation occurred at least 60% of the trials. Similar to Chapter 2, individual data was used to identify the percentage of participants who changed (or did not change) their *critical point* between conditions.

4.3.4 Statistical Analysis

Since catch trials were included in this experiment, a GLM with repeated measures was run to determine if there was an order effect. No significant effect of trial order was found and as such, the data was collapsed across trials in subsequent analysis. A 2 (obstacle type) x 9 (aperture width) x 2 (gender) GLM with repeated measures (obstacle type and aperture width) was conducted for the dependent variables described above to identify any main effects of obstacle type, aperture width and/or gender.

For all tests, a significant main effect of obstacle type or any interaction with it would indicate differences in behaviour when walking between people and poles. All *p*-values less than 0.05 were considered significant and Tukey’s post-hoc analyses were conducted for all main effects.

4.4 Results

4.4.1 Shoulder Rotations and the Critical point

When considering the *magnitude of rotation*, significant main effects of aperture width ($F_{(5, 85)} = 60.37$, $p<0.001$, $\eta^2 = 0.55$) and obstacle type ($F_{(1, 17)} = 59.69$, $p<0.001$, $\eta^2 = 0.72$) were identified (Figure 2a). Specifically, the magnitude decreased as the size of the aperture increased ($p<0.01$) and was larger when walking through the human obstacles compared to the poles ($p<0.01$; Table 2). No significant effect of gender and no significant interactions were identified. Tukey's post-hoc analysis revealed that the *magnitude of rotation* was significantly different from zero for aperture widths smaller than 1.3 for the pole obstacles ($p<0.05$) and for aperture widths smaller than 1.6 for human obstacles ($p<0.05$). This result reveals that the group *critical point* was 1.3 for poles and 1.6 for human obstacles (Figure 2b). Individual analysis revealed that 68% of the participants followed this trend. Individual *critical point* values are reported in Table 1 and a related samples *t*-test revealed that the individual *critical points* for the two conditions were significantly different from one another ($t_{(18)} = -14.57$, $p<0.001$, $d = 3.3$). Thus, the amount of shoulder rotation produced at the TOC and the subsequent *critical points* were, in general, larger when participants crossed through human obstacles than it was for passing through poles.

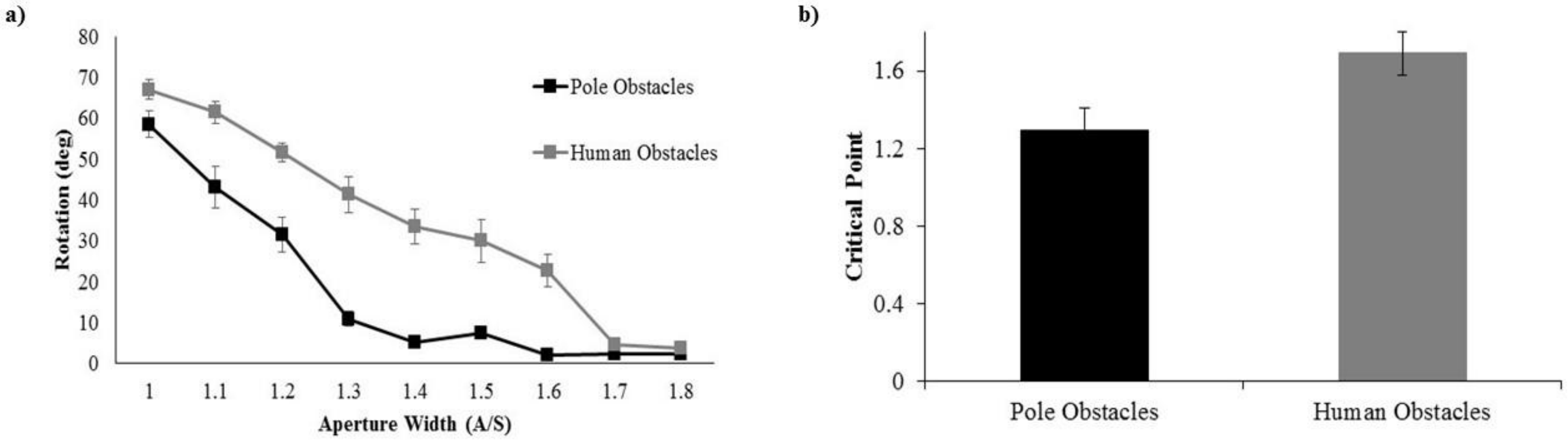

Figure 4.2 - a) *Magnitude of rotation* for both conditions. Rotations decreased as the aperture size increased (p<0.01) and were larger for passing through human obstacles (p<0.05), and **b)** the average CP for both conditions. The CP was larger for humans obstacles (p<0.05).

The significant effect of obstacle type for *magnitude of rotation* may be explained simply by the fact that individual's rotated their shoulders more frequently when passing through the confederates compared to the poles (inferred from the larger *critical point*). Therefore, we examined the *magnitude of rotation* at the *critical point* (the aperture width that corresponded to each participant's *critical point*) between the pole and human obstacle conditions. This allowed for direct comparison of shoulder rotation angle at the largest aperture width at which participants needed to rotate their shoulders. Since there was no significant effect of gender, the data was collapsed and a paired samples t-test compared the *magnitude of rotation* between the pole and human obstacle condition. Results revealed a significant difference between the two obstacle types ($t_{(19)} = -5.15$, $p<0.05$), where the rotation angle was larger at the *critical point* when passing through the human obstacles than it was for the pole obstacles.

The *onset of rotation* was analyzed in a similar manner and results revealed a significant effect of obstacle type ($F_{(1, 17)} = 12.06$, $p<0.01$, $\eta^2 = 0.56$) where individuals rotated their shoulders earlier when walking through human obstacles compared to pole obstacles. No effect of aperture width or gender (Table 4.2) was detected. Although not significant, males tended to initiate a shoulder rotation earlier (farther from the poles or confederates) compared to females ($p = 0.08$).

4.4.2 Spatial margin

When considering the *spatial margin*, analysis revealed a significant effect of aperture width ($F_{(5, 85)} = 9.87$, $p<0.01$, $\eta^2 = 0.31$) where the *spatial margin* increased as the aperture size increased (Figure 4.3). Furthermore, a significant effect of obstacle type was also identified ($F_{(1, 17)} = 11.93$, $p<0.05$, $\eta^2 = 0.65$), where the size of the *spatial margin* was larger when walking through the human obstacles compared to the pole obstacles (Table 4.2). Although there was no significant effect of gender, there was a trend for males to leave a larger *spatial margin* than females ($p = 0.09$). In the individual participant's analysis, a significant effect of obstacle type was observed for 79% of participants. Thus, participants appeared to leave more space between their shoulders and the obstacles at the TOC through human obstacles compared to the poles.

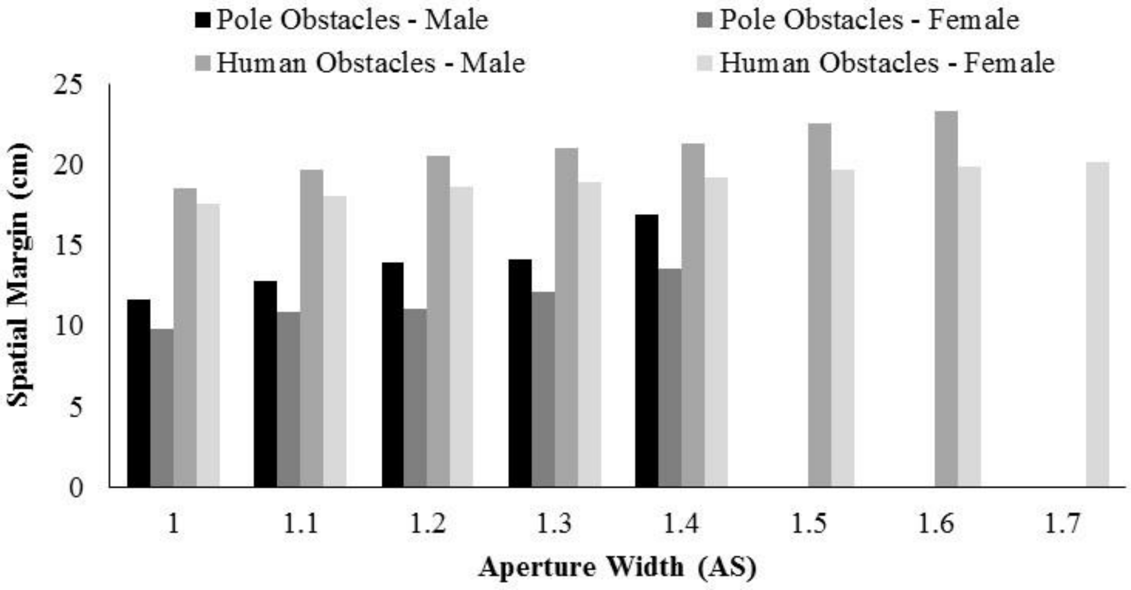

Figure 4.3 – The *spatial margin* across aperture widths for males and females in both conditions. The *spatial margin* increased as the size of the aperture increase ($p<0.01$), was larger for human obstacles compared to poles ($p<0.05$) and there was a trend for males to leave more space than females ($p=0.09$).

4.4.3 Velocity

Results revealed a significant main effect of obstacle type for both the *approach velocity* ($F_{(1, 17)} = 15.58$, $p<0.01$, $\eta^2 = 0.51$) and *velocity at TOC* ($F_{(1, 17)} = 26.66$, $p<0.01$, $\eta^2 = 0.37$). Specifically, individuals walked slower when approaching and passing through human obstacles compared to approaching and passing through the poles (Table 4.2). Significant effects of aperture width and gender were not observed for either of the velocity calculations. The results from the individual analysis revealed that all participants had a main effect of obstacle type for both *approach velocity* and *velocity at TOC*. Thus, all participants followed the trend of walking slower for human obstacles compared to poles.

In all conditions, the *velocity at TOC* did not fall outside two standard deviations of the *approach velocity*, indicating that individuals did not significantly alter their *walking speed* when passing through either the poles or the human obstacles. Therefore, further analysis of the onset of velocity changes was not pursued.

Table 4.2 - Mean, standard deviations and *p* values of dependent variables for both conditions.

Dependent Variables	**Pole Obstacles ($\bar{x}$/SD)**	**Human Obstacles ($\bar{x}$/SD)**	***p*-value**
Rotation magnitude (deg)*	36.27 (±4.61)	49.98 (±2.84)	< 0.05
Critical point	1.3	1.6	< 0.05
Onset of rotation (m)	0.47 (±0.02)	0.63 (±0.03)	<0.01
Spatial margin (cm)	10.29 (±0.78)	16.20 (±1.07)	< 0.05
Approach velocity (m/s)	1.44 (±0.13)	0.83 (±0.14)	< 0.01
Velocity at TOC	1.38 (±0.17)	0.89 (±0.15)	< 0.01

*This average only includes trials where significant shoulder rotations occurred.

4.4.4 Explaining Changes in the Critical point

Since participants increased the size of their *critical point* when walking between human obstacles, we conducted correlational analyses to help explain why these changes occurred. Pearson correlations were run to determine if the changes in the *critical point* between pole and human obstacles was related to changes in *walking speed*, height and/or social risk taking scores. The change in *walking speed* was included as a variable since research has shown that larger *critical point*s (Hackney & Cinelli, 2011; Hackney et al., 2015) and slower *walking speed*s are observed in situations of increased caution (Brown, Gage, Polych, Sleik & Winter, 2002; Hackney et.al, 2015; Pijnappels, Bobbert & van Dieen, 2001). Height was also included as a variable, as we anticipated that the location of the participant's shoulders relative to the confederate's head may influence shoulder rotations, such increased caution (i.e., more frequent shoulder rotations) would be observed when the shoulders were closer to the head. Lastly, since we hypothesized that the confederate's personal space boundaries may be considered, the scores from the social component of the risk-taking questionnaire were included in the analysis as we anticipated that the amount of risk an individual is willing to take in a social situation may influence how comfortable (or how uncomfortable) he or she is walking near another person's personal space.

The results revealed a significant positive relationship between changes in the *critical point* and changes in *approach velocity* ($r = 0.48$, $p<0.05$) (Figure 4a), and a significant negative relationship for the social component of the DOSPERT ($r = -0.65$, $p<0.01$) (Figure 4b). Specifically, larger reductions in *approach velocity* were related to larger increases in their *critical point.* Furthermore, those who scored low on the social risk-taking component of the risk-taking questionnaire had larger changes in their *critical point.* Since these three factors were correlated with changes in the *critical point*, a multiple regression analysis was conducted to determine if these variables could predict the amount of change in the *critical point*. Using the stepwise method it was found that social risk taking scores and changes in velocity explained a significant amount of the variance in the change of *critical point* ($F_{(2, 16)} = 7.49$, $p<0.05$, $R^2 = 0.70$, $R^2_{\text{adjusted}} = 0.42$). The analysis showed that both social risk taking scores (Beta = 0.69, $t_{(18)} = 3.69$, $p<0.01$) and changes in velocity (Beta = 0.40, $t_{(18)} = 2.14$, $p<0.05$) significantly predicted changes in the *critical point*.

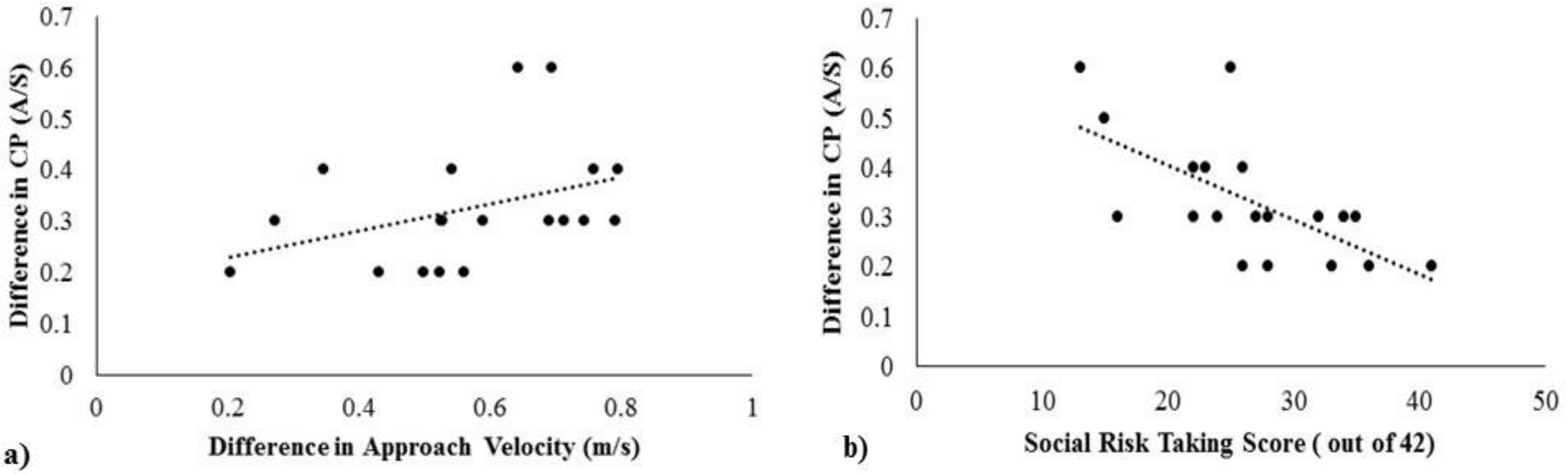

Figure 4.4 - Pearson's correlations revealed **a)** a positive relationship between differences in the *approach velocity* and differences in CP between conditions (r = 0.48, p<0.05) and **b)** a negative relationship between social risk tasking scores and differences the CP (r = -0.65, p<0.01).

4.5 Discussion

The current study set out to determine if the passability of apertures changes when walking through human obstacles compared to poles, with a specific focus on whether the *critical point* is altered for the two different obstacle types. Since research has demonstrated that individuals are good at identifying the affordances of others (Chang, Wade & Stoffregen, 2009; Creem-Regehr, Gagnon, Geuss & Stefanucci, 2013, Davis, 2009; Mark, 1997; Ramenzoni, Riley, Davis, Shockley, & Armstrong, 2008; Stoffregen, Gorday, Sheng & Flynn, 1999) and people choose to walk farther around another person or a group of people compared to an empty bench (Knowles, Kreuser, Hass, Hyde & Schuchart, 1976), we hypothesized that individuals would maintain a larger *critical point* when walking through human obstacles than they would for the poles.

In line with our hypothesis, the average *critical point* was significantly larger when walking through human obstacles compared to the poles (Figure 2b). Individual analysis revealed that all but one participant followed this trend. Similar to previous research (Hackney et al., 2013; Hackney et al., 2014; Warren & Whang, 1987), individuals deemed apertures created by two pole obstacles as passable (i.e., requiring no shoulder rotation) when the space between them was 1.3x SW or larger, but needed to rotate their shoulders for spaces smaller than this ratio. The *critical point* increased to 1.65x SW when the same participants were required to walk between human obstacles. Not only does this larger *critical point* suggest that the passability of the apertures differed between the two types of obstacles, and that individuals pass through stationary people much more cautiously than poles. In addition to the *critical point,* all other obstacle avoidance behaviours observed in the current study demonstrated greater caution for avoiding the human obstacles. Whenever participants needed to rotate their shoulders to pass through the aperture (regardless of its size), they rotated to a larger degree (Figure 2a) and maintained a larger *spatial margin* at the TOC, leaving more space between their shoulders and the obstacles (Figure 3). Although we did not observe any significant reductions in *walking speed* from the approach phase to the TOC, individuals decreased their overall *walking speed* when approaching and passing through the human obstacles by 40% compared to the *walking speed* for the poles (Table 2).

Collectively, such findings can be expected if an individual is acting more cautiously. Previous obstacle avoidance studies have observed similar effects. For example, when the penalty for error is high, individuals make more conservative decisions about whether or not they can pass through an aperture. Specifically, if the consequence of failure is falling off a ledge versus getting wedged between two obstacles individuals judge the passability of the apertures more cautiously for the situations where a potential fall is involved by reporting that they would need to rotate their shoulders for larger aperture sizes (Comalli, et al., 2013). When walking on an elevated surface (where more *trunk sway* is involved), individuals enlarge their *critical point* when passing through apertures at elevated heights compared to ground-level pathways, essentially increasing the size of the *spatial margin* (Hackney et al., 2015). Similarly, this increased *spatial margin* can also be observed when stepping over barriers on elevated surfaces (McKenzie & Brown, 2004) or when a warning about a tripping hazard has been given (Pijnappels et al., 2001). Considering the results of the above-mentioned studies, it is therefore plausible that the larger *critical point*, wider *spatial margin*s, and decreased *walking speed*s observed in the current study are indicative of a more cautious approach to passing through two humans compared to two poles. In support of this notion, correlational analysis in the current study revealed a significant positive relationship between changes in *walking speed* and differences in the *critical point* between obstacle types. Individuals who had greater reductions in their *walking speed* were more likely to have greater increases in the *critical point* (Figure 4b). Since slower *walking speed*s are related to more cautious gait (Brown et al., 2002; Tersteeg, Marple-Horvat & Loram, 2012), it is not surprising that those who displayed more cautious walking behaviour when approaching the human obstacles also employed greater caution at the TOC.

In addition to caution, it is possible that the behaviours observed for human obstacles were related to the fact that the human obstacles simply possessed human qualities (such as possesses the ability to think and move independently as well as possessing social boundaries) and that participants were accounting for the personal space requirements of others. A large body of literature has demonstrated that individuals are good at identifying and accounting for the affordances of other people (Chang et al., 2009; Creem-Regehr et al., 2013, Davis, 2009; Mark, 1997; Ramenzoni et al., 2008; Stoffregen, et al., 1999). Specifically with aperture crossing, when judging whether an aperture affords passage for oneself and another walker, individuals account for both their own and the other person's body size when making their decision (Creem – Regehr et al., 2013). This consideration also translates to physically walking through the aperture, where the body size and abilities of another adult (Davis, 2009) or a child (Chang et al., 2009) are accounted for. Although participants in the current study did not walk through the aperture alongside another person, it is possible that the ability to identify the affordance of others in a mutual setting (both people passing through) can also be transferred to an oncoming or stationary individual. In support of this idea, obstacle circumvention studies have demonstrated that individuals leave a larger personal space envelope (deviate further around) obstacles that possess movement qualities. In particular it has been observed that walkers will deviate further out of the way for a stationary person/group of people compared to an empty bench (Knowles et al., 1976) and that individuals will preserve a larger *spatial margin* around their bodies when avoiding oncoming obstacles where the movement characteristics are unknown (Gerin-Lajoie et al., 2005). Although we aimed to reduce social cues such as eye contact and facial expression by having the confederates wear sunglasses and maintain a neutral expression, participants were aware that the human obstacles could start walking (as indicated by the “catch” trials) and our results indicate that such human-like factors affected our results in a similar manner as observed by Gerin-Lajoie and colleagues (2005). Correlational analysis revealed a significant negative relationship between the social risk taking scores and differences in the *critical point*. Specifically, individuals who reported taking more risks in social situations had smaller changes in their *critical point*, meaning that these individuals were more likely to walk through smaller aperture sizes when the obstacles were humans compared to their non-risk taking counterparts.

Results such as the *spatial margin* and the onset of shoulder rotations indicated a trend for males to be more cautious than females when walking between the human obstacles. Since the confederates used in the study were female, it is possible that the relationship exists simply because the male participants treated them differently than the female participants did. Research examining gender differences for obstacle avoidance behaviours however, have found contradictory results. Gobbi and colleagues (2011) reported that females have a larger toe clearance when stepping over stationary and moving obstacles compared to males. This larger toe clearance would indicate a more cautious approach, however this is opposite of what was observed in the current study. Males maintained more space between their bodies and the obstacles when walking through human obstacles, suggesting their actions were more cautious than the females. Ozdemir (2008) found that when walking in a shopping center, males and females interacted more closely than female-female or male-male interactions. Following these results, one would expect that a male passing by a female confederate may therefore leave less space at the TOC. However, our results indicate that the male-female interaction resulted in larger interactions than the female-female interaction. The results from the social-risk taking scores may help explain the gender differences observed in the current study and why males tended to leave more space than females at the TOC. An independent t-test revealed that males reported taking less risks in social situations than females. Since the confederates were unknown to the participants (i.e., they had never met prior to the experiment), it is possible that the males deemed this close encounter with an unknown female as more socially risky than the female participants. Future research should consider examining aperture crossing behaviours when the aperture is created by two males or a male/female combination to differentiate the role that gender may play between people and under a variety of social situations such as when the confederates are known to the participants or when the confederates are engaging in a conversation. The fact that social risk-taking scores were so highly correlated with changes in the *critical point* suggests that the larger *spatial margin*s needed for walking through human obstacles are likely influenced by social factors. Future research should focus on identifying what factors contribute to this effect.

Lastly, on a random set of trials, the human obstacles unexpectedly began walking toward the participant. These catch trials were included to remind participants that the human obstacles still had human-like qualities (such as the capability of movement) and to represent a more realistic obstacle avoidance environment, since it would be very rare for human obstacles to have absolutely no potential for movement. As a consequence however, behaviour may have been influenced by these walking trials that may not have existed if movement trials were not included. For example, participants may have acted more cautiously if they were aware that the obstacles may begin to move. However, the results revealed no significant differences in behaviours based on trial order, which would suggest that the catch trials did not immediately influence behaviour.

4.6 Conclusions

The findings of the current study suggest that the passability of apertures is different for human and pole obstacles. Specifically, individuals maintain a larger *critical point* and pass through the aperture more cautiously when the space is created by human obstacles. This larger *critical point* likely occurs because the walker is accounting for the human-like qualities (such as movement, personal space boundaries and social factors) that the human obstacles retain but which do not exist for the poles.

4.7 Additional Notes

One of the main methodological challenges I faced when I was originally developing study three was that experimental manipulations involving human obstacles proved to be much more difficult to maintain than pole obstacles. Ensuring that the various aperture widths for the human obstacle condition remained consistent throughout the experiment was especially difficult during the “catch” trials, where the confederates walked toward the participant. Originally, I had planned on comparing the aperture crossing behaviour of stationary human obstacles to that of moving ones but because of inconsistencies with aperture width, the data from these “catch” trials were removed from further analyses.

After the completion of the experiment, I had the opportunity to visit Brown University’s Virtual Environment Laboratory directed by Dr. William Warren. The VEN lab has a unique virtual reality environment, where participants can move freely throughout a 12m x 12m open space while wearing a head-mounted display (HMD) that updates the virtual scene as the individual moves throughout the space. Perhaps aperture crossing in a virtual environment could elicit similar differences between human and pole obstacles (or avatar and virtual poles) as observed in the real-world study. If so, virtual reality may provide a solution to the challenges associated with using human obstacles which would be especially useful for future studies looking to examine complex pedestrian environments where the human-aperture is also moving. As such, the small follow-up study that resulted from my visit to the VEN lab is presented at the end of this document (see Supplementary Material) and examines aperture crossing behaviour in a virtual reality environment.

- Chapter 5 -

ACTION STRATEGIES FOR WALKING THROUGH MULTIPLE, MISALIGNED APERTURES

Connective Statement

In an effort to create a more realistic environment, I originally conducted a “crowded room” experiment where participants (N = 52) simply walked to a goal while navigating through a crowd of people. In a 7m x 4m space, 14 volunteers acted as “human obstacles” and stood at a specific location with their heads down (Appendix E). Human obstacles were used in this experiment because the results outlined in Chapter 4 demonstrated that individuals walk through narrow spaces created by other people much differently than they walk through pole obstacles. Although technical difficulties prevented full data analysis, initial observations revealed that participants appeared to utilize one of two strategies. In some instances, individuals seemed to treat each aperture separately and would deviate away from the straightest walking path in order to pass through the center of an aperture with as little shoulder rotation as possible. In others, participants maintained a large rotation throughout the entire trial and appeared to “snake” through the apertures, passing much closer to one side of the aperture than the other.

From these observations I was left wondering; (1) what strategies individuals use when walking through multiple, misaligned apertures, (2) how multiple aperture crossing is different from single aperture crossing, and (2) which aspects of the path is acting as the attraction point when guiding path trajectory*:* the end-goal or the center of the aperture. Chapter 5 presents the results of a multiple and misaligned aperture crossing study designed to address these questions.

5.1 Abstract

Individuals attempt to equalize the amount of space between the shoulders and the obstacles, by walking through the center of an aperture (Cinelli, Patla & Allard, 2008) The behavioural dynamics model argues that since path selection is determined by the attraction of the end-goal, individuals walk through the center of the aperture because the attraction is pulling them there (Fajen & Warren, 2003). However for aperture crossing, it is unclear whether the attraction originates in the center of the aperture or the end-goal. The purpose of the current study was to decipher the possible location of the attraction point, by evaluating crossing behaviour for multiple, misaligned apertures. Participants were instructed to walk through three apertures towards an end-goal. The first and last apertures were fixed such that they were both either 0.9x or 1.7x SW, the second aperture was either 0.9, 1.3 or 1.7x SW and shifted 25, 50 or 75cm off the midline of the path. Participants were permitted to rotate their shoulders if they felt inclined to do so. Findings revealed that the attraction of the end-goal, and not the middle of the aperture, guided crossing behaviour evident by the fact that the COM position at the TOC was closer to the obstacle nearest midline and the *spatial margin* decreased as the size of the shift increased. Furthermore, the *frequency of rotation* increased as the shift of the middle aperture increased, regardless of the aperture size. Since rotations would not normally occur for all of these aperture sizes when they are aligned with the end-goal, these results suggest that rotations were produced in an attempt to keep one's trajectory as close to the midline as possible. Therefore, not only does the attraction of the goal guide path trajectory, but individuals will choose to reduce the *spatial margin* and rotate the shoulders when walking through misaligned apertures, likely in attempt to maintain the straightest possible path.

5.2 Introduction

The behavioural strategies involved for successfully walk through an aperture on the travel path are well documented. First, individuals initiate a shoulder rotation for apertures deemed too small for straight passage and scale the size of the rotation to the size of the aperture (Franchak et al., 2010; Hackney & Cinelli, 2013b; Warren & Whang, 1987; Wilmut & Barnett, 2010). Second, the amount of rotation produced at TOC is controlled by the desire to maintain a minimal *spatial margin* between the shoulders and the obstacles (Higuchi et al., 2009). Lastly, adjustments to both the path trajectory and *walking speed* are made in order to approach an aperture head-on and pass through the center of it, likely in an attempt to equalize the size of the *spatial margin* for both shoulders (Cinelli et al., 2008; Higuchi, Cinelli, Greig & Patla, 2006).

The fact that individuals adjust their actions in order to cross through the center of an aperture is in direct line with the visual equalization strategy. Srinivasan and colleagues (1991) first introduced the idea of flow equalization by observing that honeybees fly along a corridor in a location where the speed of optic flow from each wall reaches the lateral portion of the eyes at equal rates. The honeybee therefore aims to fly along the optic flow balance point. Moreover, if artificial motion is added to one wall, the bee will adjust its position in order to fly down the path in a location that is perceived as having equal flow speeds (Srinivasan, Lehrer, Kirchner & Zhang, 1991). The idea of a flow equalization control law has also been implemented as a means of guiding robots through cluttered environments. By following such a control law, the mobile robots were able to traverse down passageways, through openings and around obstacles with considerable success (Coombs, Herman, Hong & Nashman, 1998; Duchon & Warren, 1994; Duchon, Warren & Kaelbling, 1998; Weber, Venkatesh & Srinivasan, 1997). More current research has extended these findings by demonstrating that humans also employ a similar strategy when walking down corridors (Duchon and Warren, 2002; Dyre & Andersen, 1996) and as mentioned previously, through apertures (Cinelli et al., 2008; Higuchi et al., 2006).

In addition to equalizing the speed of optic flow, research has suggested that human locomotion is also guided by the attraction pull of goals and the repulsion force of obstacles. Fajen and Warren (2003) argue that path trajectory towards a goal and around obstacles is a function of the relative angles between the heading and the instantaneous relative positions of the goals and obstacles, which act as attractors and repellers. In other words, the travel path is determined by the attraction pull of the goal and the repulsion force of the obstacles to be avoided. Although obstacles push an individual off the straight walking trajectory, the attraction of the goal quickly pulls them back so that a walker can reach his or her goal by walking the straightest path possible (Warren, 2006). Therefore, when traversing a corridor or walking through narrow passageways, the attraction of the goal and the flow equalization strategy are both likely to guide an individual down the center of the passage way. However, since previous studies involve experimental set-ups where the aperture is located in direct line with the goal, it is unclear the extent to which both strategies guide aperture crossing behaviours. One cannot decipher whether individuals are equalizing the *spatial margin* of the shoulders at TOC because the attraction point is first located at the aperture itself or because they are aligning themselves with the attraction pull of the end-goal. In other words, do individuals treat aperture crossing as a two-step process whereby the center of the aperture is the first goal or is the end-goal is the sole attraction point?

Although a substantial body of literature exists to explain how individuals adjust their actions to walk through single apertures, the examination of multiple aperture crossing is far less common despite the fact that navigating through crowds of people encompasses a series of various-sized, and potentially misaligned, apertures. Not only is research needed to determine the action strategies employed for multiple aperture crossing, but these scenarios can also help determine what aspect of the travel path acts as the attraction point. Therefore the current study set out to explore how individuals walk through a series of apertures that vary in both their size and their position on the walking path.

If the attraction point is first located at the aperture (before moving to the end-goal once the individual arrives at the aperture), then individuals will be attracted to the center of the aperture and act to equalize the *spatial margin* between the shoulders and the obstacles at TOC. As observed with single aperture crossing, this equalization will be achieved by deviating away from the straight walking path and approaching the aperture head-on (Cinelli et al., 2006). If the equalization strategy is the dominant control strategy also used for misaligned aperture crossing, then one would also anticipate that as the size of the off-set increases, the path deviations will move away from midline in order for the position of the COM to always pass through the center of the aperture. However, if the final end-goal acts as the only attraction point, then the multiple apertures may be treated as a steering task where the individual guides behaviour through a winding path while circumventing obstacles. As such, individuals may opt to maintain the straightest possible path through the apertures by walking closer to the obstacle nearest the midline rather than walking to the center of each aperture. As the size of the off-set increases, one would expect that the position of the COM relative to the center of the aperture to increase and the size of the *spatial margin* to decrease. In some instances, this may result in individuals choosing to rotate their shoulders for apertures shifted off midline for spaces where a shoulder rotation may not normally be necessary.

The purpose of the current study to decipher whether multiple aperture crossing is perceived as having the attraction point be the center of the aperture or the final end-goal. To do this, participants were asked to walk through three separate apertures of various sizes and the second aperture was shifted away from the midline of the path. It was hypothesized that behaviour would be similar to that predicted from a single end-goal attraction point, whereby the desire to maintain the straightest possible walking path would override the desire to walk through the center of the aperture. Therefore, it was anticipated that the M-L COM position relative to the center of the aperture would increase and the *spatial margin* would decrease as the size of the off-set increased. Additionally, we anticipated that participants would rotate their shoulders more frequently as the size of the shift increased, even at aperture widths that would not normally induce a shoulder rotation.

5.3 Methods

5.3.1 Participants

Nineteen healthy YA ($\bar{x}_{\text{age}}$ = 23.31 ± 2.67 years; 9 males and 11 females) volunteered to participant in the study (Table 5.1). In order to confirm eligibility, all participants completed a health screening questionnaire prior to the experiment (Appendix B). In line with the inclusion/exclusion criteria maintained throughout the dissertation, participants were included in the study if they were free of deficits or disorders affecting balance and locomotion; had no hip, knee or ankle injuries within the last two years; and had normal or corrected-to-normal vision.

Once informed and written consent was obtained, the researchers recorded the shoulder width of each participant using a measuring tape. Ethics approval was obtained from the University of Waterloo's Office of Research Ethics and the Wilfrid Laurier University Research Ethics Board.

Table 5.1 – Participant characteristics included age, gender and SW.

Participant	Gender	Age (yrs)	SW (cm)
1	F	21	41.5
2	M	22	46.0
3	F	25	42.0
4	F	19	41.5
5	F	24	43.0
6	M	25	48.5
7	M	22	49.5
8	M	22	50.0
9	M	19	46.5
10	M	20	47.5
11	M	23	45.5
12	F	24	42.0
13	F	24	41.0
14	M	27	47.5
15	M	28	45.5
16	F	24	42.5
17	F	27	40.0
18	F	21	40.5
19	M	26	45.0
Average/SD	**-----------**	***23.3 ±2.66***	***44.5 ±3.18***

5.3.2 Apparatus

The experiment was conducted on an 11m long path with three sets of pole obstacles (0.23m W x 2.4m H) located 3.5m, 5.5m and 7.5m from the starting location (Figure 5.1). Each set of poles created an aperture for the participants to walk through, which could be manually adjusted by the researchers. For all trials, participants were instructed to walk to the goal located at the end of the path and pass through all three apertures without colliding with the obstacles. Furthermore, participants were instructed to rotate their shoulders when passing through spaces they felt were too narrow for straight passage. Avoiding the apertures all together by walking around them was not permitted. Between experimental trials, participants faced away from the path while the researchers manually adjusted the size of the three apertures.

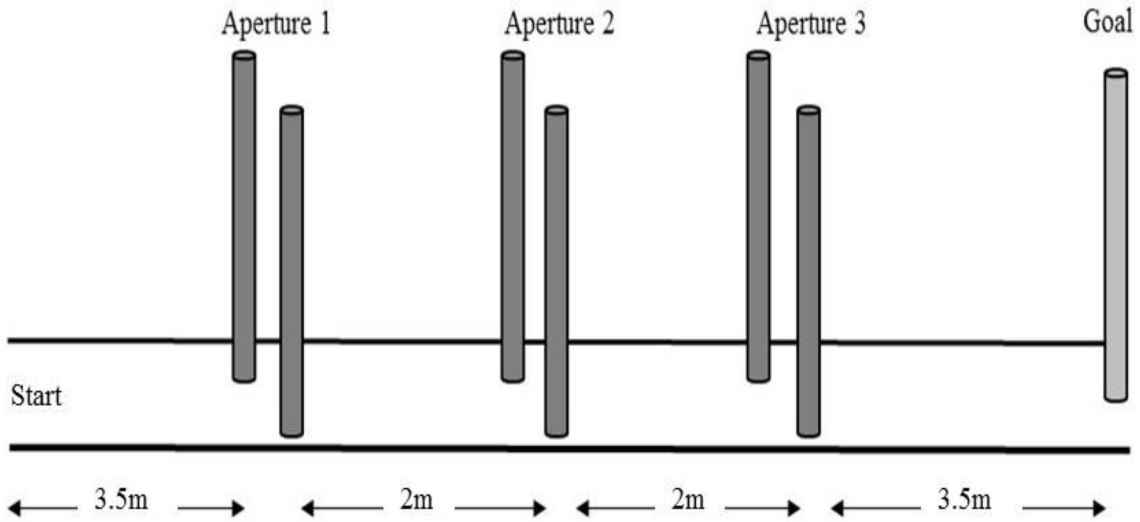

Figure 5.1 – A sagittal view of the experimental set-up, including the three apertures which were located 3.5, 5.5 and 7.5m from the starting location.

Kinematic data was measured using the OptoTrak camera system (Northern Digital Inc., Waterloo, ON. Canada) at a sampling frequency of 60Hz. IRED markers were placed on the external occipital protuberance, the left and right posterior-lateral aspects of the spinous process of the scapula and tenth thoracic vertebrae (Appendix C).

5.3.3 Experimental Design

On all experimental trials, both the first and the last aperture were located directly in line with the goal such that the center of the aperture aligned with the midline of the path. Throughout the experiment, the size of these two apertures were presented as a pair (i.e., both aperture widths were equal) and set at either 0.9x or 1.7x SW. The second (middle) aperture was randomly presented as either 0.9, 1.3 or 1.7x SW. Furthermore, the second aperture was also randomly shifted such that the center of the aperture was located 25, 50, or 75cm away from the midline of the path (Figure 5.2). Therefore, on any given trial, the first and last aperture could be 0.9 or 1.7x SW, the second aperture could be 0.9, 1.3 or 1.7x SW and shifted 25, 50 or 75cm off midline. Half of the participants experienced the second aperture shifting to the left of midline while the other half had shifts to the right. Two baseline conditions were also included in the experiment, where all three apertures were presented as the same size (0.9 or 1.7) and aligned with one another (i.e., the second aperture was not shifted).

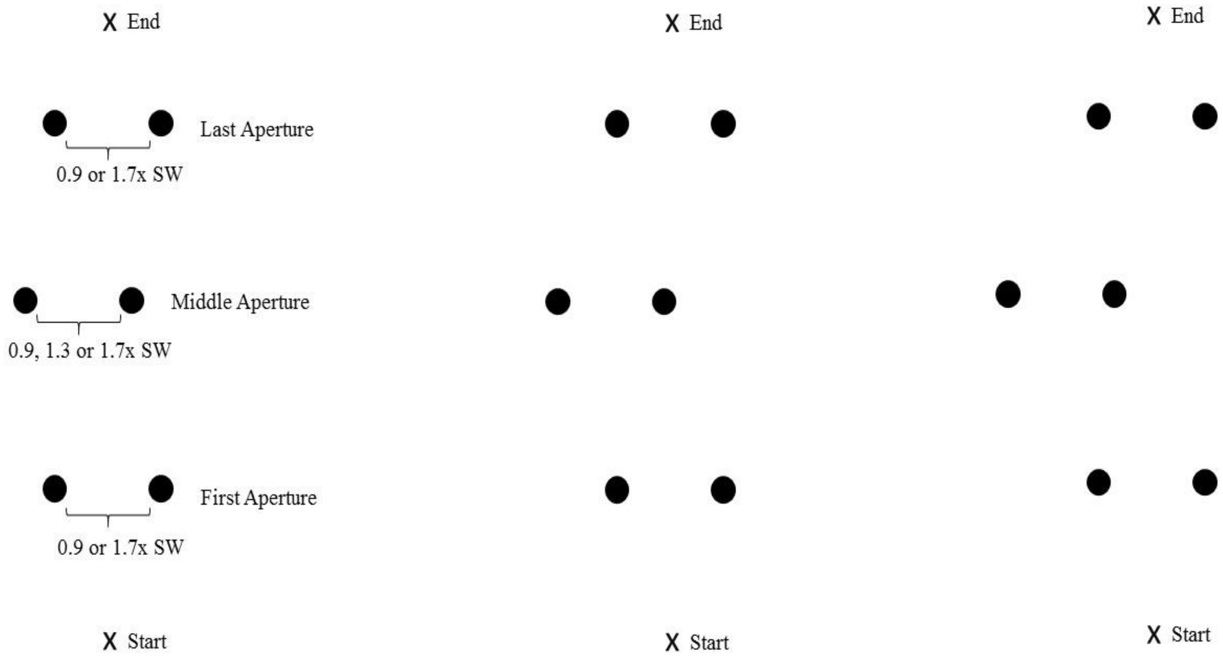

Figure 5.2 – An example of the experimental set-up, including the three possible shifts of the second aperture: 25, 50 or 75cm from the midline of the path.

5.3.4 Data Analysis

The location of each participant's A-P and M-L COM was estimated using the IRED markers on the torso in the same manner outlined in previous chapters (Appendix C). Since the experiment was designed to determine how a shift in the aperture's location from midline affects crossing behaviour, the majority of dependent variables were calculated at the TOC the second aperture since this was the aperture that was shifted away from midline. Both the position of the M-L COM relative to the center of the aperture (*distance from center)* and the *spatial margin* were analyzed to determine which aspect of the path acted as the attraction point. *Spatial margin* was calculated in the same manner as outlined in Chapter 2 (Section 2.3.5). *Distance from center* was also determined for the first and third apertures in the baseline walking trials (0.9 and 1.7x SW only) to confirm that during the aligned aperture crossing, participants aimed to walk through the center of the aperture.

Additionally, the *magnitude* and *frequency of rotation,* and *velocity at TOC* were analyzed when the participant crossed the second aperture. The *frequency of rotation* was also calculated for the first and third apertures during the baseline trials (0.9 and 1.7x SW only). It was important to determine this behaviour, as the purpose of including multiple apertures was to set up a condition in which an individual had to rotate their shoulders prior to reaching the second aperture and another condition in which no prior rotations were necessary. This was conducted to confirm that shoulder rotations were produced for apertures that were 0.9x SW but not for 1.7x SW. The methods used to calculate these variables are described in Chapter 2 (Section 2.3.5) and are visually represented in Appendix A. Additionally, the average *walking speed* throughout the entire trial was calculated by using the change in displacement of the A-P

COM over time. The average velocity from the start to the end of the trial was used instead of the *approach velocity* because the location of the first aperture removed the typical 2m approach used in previous chapters.

5.3.5 Statistical Analysis

Confirming Baseline Behaviour

To confirm that shoulder rotations occurred for small apertures (0.9x SW) and not for larger apertures (1.7x SW) during the baseline trials, the *frequency of rotation* data at all three apertures was first converted to parametric data using an arcsine transformation and run through a 3 (aperture location: first, second or third) x 2 (aperture size: 0.9 or 1.7x SW) GLM with repeated measures. Using the same statistical test, the *distance from center* data was analyzed to confirm that the participants aimed to walk through the center of the aperture(s) when they were aligned with the end-goal. *P*-values of 0.05 were considered significant.

Does the direction of shift influence aperture crossing behaviours?

Half of the participants walked through the second aperture when it was shifted to the left, while the other half experienced a rightward shift. To determine whether the direction of the shift influenced crossing behaviour, the *distance from center* and *spatial margin* at the second aperture was run through a 2 (shift direction; left or right) by 3 (aperture size: 0.9, 1.3, or 1.7x SW) x 3 (shift size; 25, 50, or 75cm) GLM with repeated measures. A null finding would allow data to be collapsed across shift direction in future analyses.

Do individuals pass through the center of an aperture when it is not aligned with the end-goal?

In order to determine whether the attraction point is the middle of the aperture or the final end-goal, the *distance from center* and *spatial margin* data collected at the second aperture was used for analysis. The two baseline conditions were excluded from this analysis. A 2 (first aperture size; 0.9 or 1.7x SW) x 3 (second aperture size; 0.9, 1.3 or 1.7x SW) x 3 (shift size; 25, 50 or 75cm) GLM with repeated measures was conducted for each variable to determine whether individuals walked through the center of the aperture or if they preferred to walk closer to the obstacle closest to midline. A null finding would indicate that individuals aimed to walk through the center of the aperture and/or maintain a similar-sized *spatial margin* for all experimental manipulations. *P*-values of 0.05 were considered significant.

How are shoulder rotations influenced by the size of the first aperture and/or the size and shift of the second aperture?

This analysis was conducted to determine whether rotating the shoulders at the first aperture influenced the behaviour at the second and whether the location of the second aperture altered rotation behaviour. To answer these questions the *magnitude of rotation* at the second aperture was run through a 2 (first aperture size: 0.9 or 1.7x SW) x 3 (second aperture size: 0.9, 1.3 or 1.7x SW) x 3 (shift size: 25, 50 or. 75cm) GLM with repeated measures. Additionally, the *frequency of rotation* at the second aperture was converted to parametric data through an arcsine transformation. It is important to note that for the purpose of analysis of the *frequency of rotation*, data for aperture size 0.9x SW was removed from analysis. This is because at 0.9x SW, rotations occurred 100% of the time, regardless of shift or size of the first aperture. As such, including this data in the analysis risked washing out any effects of the experimental manipulations as participants had reached a ceiling performance. Therefore, the *frequency of rotation* was run through a 2 (first aperture size: 0.9 or 1.7x SW) x 2 (middle aperture size: 1.3 or 1.7x SW) x 3 (shift: 25, 50 or 75cm) GLM with repeated measures. *P*-values of 0.05 were considered significant.

Does the size of the first aperture, the size of the second and/or the size of the shift influence walking speed?

In order to determine whether the experimental manipulations effected the speed at which individuals completed the task, 2 (first aperture size; 0.9 vs. 1.7x SW) x 3 (second aperture size; 0.9, 1.3 vs. 1.7x SW) x 3 (shift size; 25, 50 vs. 75cm) GLM with repeated measures was conducted for *velocity at TOC* and average *walking speed.* A null finding would indicate that individuals walked the path at the same speed regardless of the size of the first or second aperture or how much the second aperture was shifted from midline. *P*-values of 0.05 were considered significant.

5.4 Results

5.4.1 Confirming Baseline Behaviour

A 3 (aperture location) x 2 (aperture size) GLM with repeated measures was used to confirm that shoulder rotations were produced for small apertures but not large ones. The analysis identified a main effect of aperture size ($F_{(1, 18)} = 159.09$, $p<0.001$, $ŋ^2 = 0.89$) such that shoulder rotations occurred significantly more often when the aperture was 0.9x SW (100% of trials) compared to 1.7x SW (0% of trials). There was no main effect of aperture location (first, second or third), suggesting that all apertures were treated the same (Table 5.2). Therefore, individuals rotated their shoulders the same number of trials at each aperture on the travel path when all three apertures were aligned with the end-goal, but rotated more often at apertures 0.9x SW compared to 1.7x SW.

When considering *distance from center*, a second 3 (aperture location) x 2 (aperture size) GLM with repeated measures revealed no main effect of aperture size or aperture location. On average, participants walked 1.72cm (±0.09cm) from the center of the aperture regardless of its size or its location (Table 5.2).

Table 5.2 – Means and standard deviations for the baseline conditions including *distance from center* and *magnitude of rotation*.

Baseline Condition	**Distance from Center (cm)** $\bar{x}$ **(SD)**			**Magnitude of Rotation (cm)** $\bar{x}$ **(SD)**		
	First Aperture	**Middle Aperture**	**Last Aperture**	**First Aperture**	**Middle Aperture**	**Last Aperture**
All apertures 0.9	1.62	1.70	1.68	44.29	43.97	48.20
No shift	(0.02)	(0.03)	(0.03)	(13.31)	(16.7)	(11.2)
All apertures 1.7	1.64	1.69	1.73	2.48	1.98	2.01
No shift	(0.04)	(0.02)	(0.02)	(0.72)	(0.51)	(0.83)

5.4.2 Effects of experimental manipulations

Does the direction of shift influence aperture crossing behaviours?

The 2 (shift direction) x 3 (aperture size) x 3 (shift size) GLM with repeated measures found no significant effect of shift direction for *distance from center* ($p = 0.61$) or *spatial margin* ($p = 0.49$). Therefore, data was collapsed across shift direction (left or rightward shifts) for the remainder of the analysis.

Do individuals pass through the center of an aperture when it is not aligned with the end-goal?

The results of the 2 (first aperture size) x 3 (second aperture size) x 3 (shift size) GLM with repeated measures for *distance from center* identified a main effect of shift ($F_{(2, 36)} = 362.33$, $p<0.001$, $\eta^2 = 0.95$), such that participants walked farther away from center of the aperture as the size of the shift increased. There was no significant effect of first aperture size ($p= 0.09$) or second aperture size ($p= 0.34$). Figure 5.3a displays the average *distance from center* across shift size and for each second aperture size. Data is collapsed across first aperture size. Means, standard deviations and *p*-values are presented in Table 5.3.

A 2 x 3 x 3 GLM with repeated measures was also conducted to determine if the *spatial margin* was affected by the first aperture size and/or the size and shift of the second aperture. Results revealed main effects of the second aperture size ($F_{(2, 36)} = 80.51$, $p<0.001$, $\eta^2 = 0.82$) and shift ($F_{(2, 36)} = 52.47$, $p<0.001$, $\eta^2 = 0.75$) such that the *spatial margin* decreased as the aperture size increased and decreased as the shift increased (Figure 5.3b). First aperture size revealed no significant effect on the behaviour at the second aperture ($p= 0.35$). Means, standard deviations and *p*-values are outlined in Table 5.3.

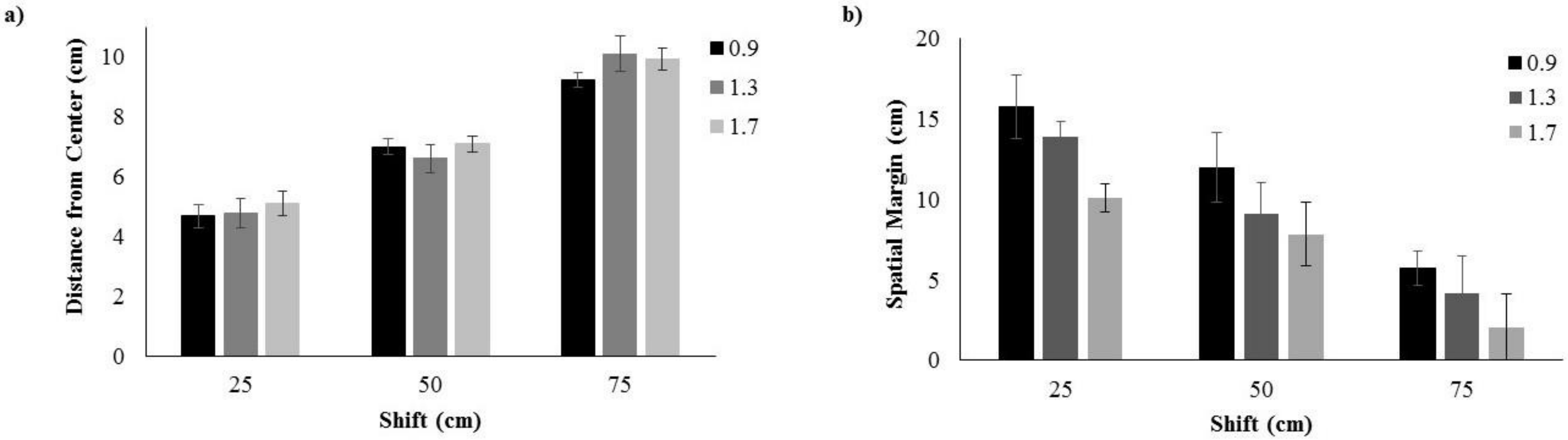

Figure 5.3 – The **a)** *distance from center* and **b)** *spatial margin* at the second aperture as a function of second aperture size and shift size. Data was collapsed across first aperture size.

How are shoulder rotations influenced by the size of the first aperture and/or the size and shift of the second aperture?

Not surprisingly, the 2 (first aperture size) x 3 (second aperture size) x 3 (shift size) GLM with repeated measures revealed a main effect of second aperture size for the *magnitude of rotation* ($F_{(2, 36)} = 112.62$, $p<0.001$, $ŋ^2 = 0.86$). Rotations increased as the size of the second aperture decreased. Interestingly, rotations at the second aperture were also affected by the size of the first aperture ($F_{(1, 18)} = 4.57$, $p<0.05$, $ŋ^2 = 0.21$) such that individuals rotated their shoulders more at the second aperture if the first aperture required a shoulder rotation (i.e., 0.9x SW). Furthermore, a significant effect of shift was found ($F_{(2, 36)} = 11.25$, $p<0.001$, $ŋ^2 = 0.40$) such that the *magnitude of rotation* at the second aperture increased as the size of the shift increase (Figure 5.4). A three-way interaction was also identified as significant ($F_{(4, 72)} = 41.36$, $p<0.001$, $ŋ^2 = 0.69$) and post-hoc analysis revealed that the same condition driving the three-way interaction for *spatial margin* was also driving the interaction for *magnitude of rotation* (first aperture 1.7, second aperture 1.3, shift 25cm). Specifically, the *magnitude of rotation* was larger when shifted 25 compared to 50 and 75cm but followed the trend of the other conditions (increasing as shift increases) when the first aperture was 0.9x SW. Means, standard deviations and p-values are reported in Table 5.3.

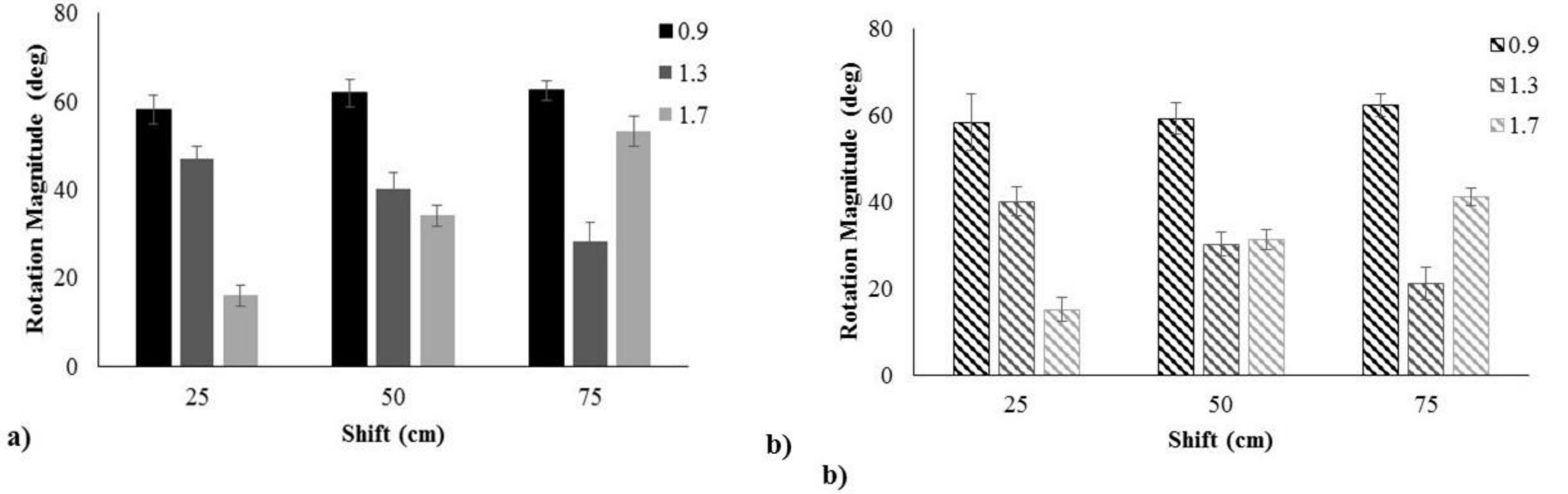

Figure 5.4 – The *magnitude of rotation* as a function of second aperture size and shift when **a)** the first aperture was 0.9x SW, and **b)** the first aperture was 1.7x SW.

Supporting the effects observed for the *magnitude of rotation*, the 2 x 3 x 3 GLM with repeated measures for the *frequency of rotation* revealed a significant effect second aperture size ($F_{(2, 36)} = 65.24$, $p<0.001$, ŋ^{2} = 0.86) and shift size ($F_{(2, 36)} = 15.21$, $p<0.01$, ŋ^{2} = 0.53). First aperture size did not significantly impact how often an individual rotated his or her shoulders at the second aperture (Table 5.3). Post-hoc analysis showed that participants rotated their shoulders more often at the second aperture at smaller aperture sizes (both the first and second apertures) and when the shift was larger ($p<0.05$ for all comparisons). Furthermore, a significant two-way interaction was revealed for middle aperture size and shift ($F_{(2, 36)} = 11.85$, $p<0.05$. ŋ^{2} = 0.47), such that the *frequency of rotation* increased as the shift increased when the aperture size was large (1.7x SW) but decreased when the aperture size was small (1.3x SW) (Figure 5.5)

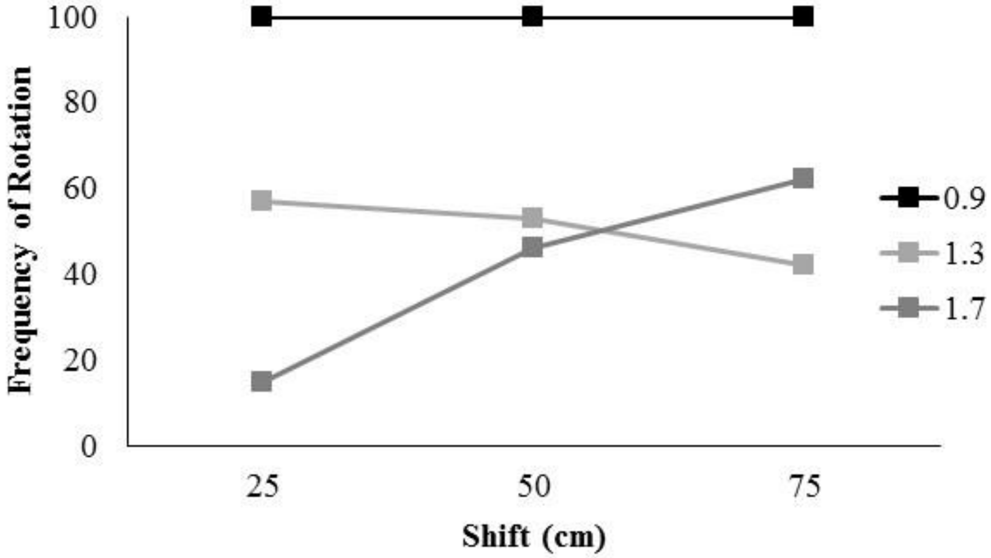

Figure 5.5 – The *frequency of rotation* as a function of second aperture size and shift. Data is collapsed across first aperture size since there was no statistical difference between the two conditions. Note that aperture 0.9 was not included in the statistical analysis but the data is included here for visual comparison purposes.

Does the size of the first aperture, the size of the second and/or the size of the shift influence walking speed?

The *velocity at TOC* the second aperture and the average *walking speed* were each run through a 2 (first aperture size) x 3 (second aperture size) x 3 (shift size) GLM with repeated measures. Results revealed a significant effect of second aperture size for *velocity at TOC* ($F_{(2, 36)} = 21.26$, $p<0.05$, $ŋ^2 = 0.45$) and average *walking speed* ($F_{(2, 36)} = 15.39$, $p<0.01$, $ŋ^2 = 0.42$). Shift size was also significant for both *velocity at TOC* ($F_{(2, 36)} = 14.01$, $p<0.05$, $ŋ^2 = 0.34$) and average *walking speed* ($F_{(2, 36)} = 9.38$, $p< 0.05$, $ŋ^2 = 0.31$). Post hoc analysis revealed that participants walked slower as the aperture size decreased and as the size of the shift increased for both variables. Not surprisingly, first aperture size had no effect on the speed at which participants crossed the second aperture (*velocity at TOC).* However, the first aperture size was significant for the average *walking speed* ($F_{(1, 18)} = 8.59$, $p<0.05$, $ŋ^2 = 0.30$), such that the average speed was slower when the first aperture was 0.9x SW compared to 1.7x SW (Table 5.3).

Table 5.3 – Means and standard deviations for *magnitude of rotation, spatial margin, distance from center* and average *walking speed* at the second aperture based on first aperture size, second aperture size and shift.

Variable	**First Aperture Size (x SW)**		**Second Aperture Size (x SW)**			**Shift (cm)**		
	0.9x	**1.7x**	**0.9x**	**1.3x**	**1.7x**	**25**	**50**	**75**
Magnitude of Rotation (deg)	31.7 (7.3)	25.3 (5.2)	60.2 (4.1)	32.3 (4.9)	30.1 (3.7)	27.6 (6.3)	30.4 (3.9)	33.4 (4.2)
Spatial Margin (cm)	3.3 (0.8)	2.7 (1.1)	5.7 (2.1)	7.1 (2.9)	11.3 (3.2)	13.1 (2.2)	9.7 (1.7)	5.3 (2.8)
Distance from Center (cm)	5.3 (1.3)	4.8 (2.6)	5.1 (2.2)	6.7 (1.7)	8.3 (2.8)	4.0 (0.7)	6.2 (1.4)	9.1 (2.0)
Walking speed (m/s)	1.12 (0.21)	1.39 (0.09)	1.15 (0.07)	1.24 (0.12)	1.40 (0.14)	1.21 (0.09)	1.35 (0.13)	1.44 (0.07)

5.5 Discussion

The current experiment set out to identify how individuals walk through multiple, misaligned apertures. Specifically, this study aimed to decipher whether the aperture acts as the attraction point for guiding locomotion or if the end-goal guides the behaviour. To test this, three separate apertures of various widths were placed on the travel path to present situations in which shoulder rotations were or were not required to pass through the apertures safely. Furthermore, the middle aperture was shifted away from the midline of the travel path so as not to be aligned with the end-goal (Figure 5.2). This was done to ensure that participants would have to deviate off the straight walking path in order to pass through one of the three apertures. If the aperture was acting as the attraction point (Cinelli et al., 2008; Higuchi et al., 2006), then individuals would likely modify their path trajectory in order to pass through the center of second aperture, equalizing the *spatial margin* between each shoulder regardless of how far it was shifted off the midline. However if the end-goal was the attraction point, then the priority may have been to maintain a straight path trajectory by walking closer the obstacle nearest midline rather than maintain an equal *spatial margin*. It was hypothesized that individuals would complete the task in a similar manner to that predicted by an end-goal attraction point, whereby the desire to maintain the straightest possible walking path would override the desire to walk through the center of the aperture. Therefore, it was anticipated that the M-L COM position relative to the center of the aperture would increase *(distance from center)* and the distance between the shoulder and the obstacle at TOC (*spatial margin)* would decrease as the shift of the second aperture increased. Additionally, we anticipated that participants would rotate their shoulders more frequently as the size of the shift increased, even at aperture widths that would not normally induce a shoulder rotation.

All participants completed the task without colliding with the obstacles and as hypothesized, the results indicate that individuals are likely guided by the attraction of the end-goal and not each aperture. This was demonstrated in two ways: 1) the size of the *spatial margin* between the shoulder and the obstacle closest to midline decreased as the aperture was shifted away from midline (Figure 5.3b), and 2) the M-L COM at the TOC (*distance from center)* moved farther from the center of the aperture and closer to the midline of the path as the shift increased (Figure 5.3a). Additionally, the *frequency of rotation* increased as the size of the shift increased: individuals rotated their shoulders more often the more the second aperture was shifted (Figure 5.5). In general, these findings suggest that the attraction of the end-goal guides path trajectory during multiple aperture crossing, and that individuals prefer to reduce the size of their *spatial margin* and rotate the shoulders when walking through misaligned apertures, likely in an attempt to maintain the straightest possible walking path.

Both the obstacle circumvention and single aperture crossing literature suggest that modifications to actions are made in order to maintain a constant *spatial margin.* Research has demonstrated that for obstacle circumvention, an elliptical-shaped protective zone is maintained around the body, regardless of the speed at which the object is approaching (Cinelli & Patla, 2005) or whether the object's movement characteristics are known (Gerin-Lajoie et al., 2008).

As such, individuals will initiate deviations away from the midline of the path in order to ensure a *spatial margin* in the A-P direction and will walk far enough away from the midline to ensure a sufficient M-L *spatial margin*. Similar behaviours are also observed for aperture crossing such that the onset and *magnitude of shoulder rotation* produced at TOC are controlled by the desire to ensure a sufficient *spatial margin* (Higuchi et al., 2012). If the aperture is of such a size where maintenance of this margin is not afforded when walking straight though, then individuals will produce a shoulder rotation or choose to avoid the space all together by walking around it. Even if individuals opt to walk around an aperture rather than walk through and rotate the shoulders, an elliptical-shaped protective zone is still maintained as the individual passes by the aperture (Hackney et al., 2013). In this case, adjustments to the current actions are made in a similar manner to that of obstacle circumvention. Together, these studies suggest that a prominent control strategy for both single aperture crossing and single obstacle circumvention is to maintain the *spatial margin.* However, the results of the current study suggest that when the additional component of a misaligned aperture is added to increase the complexity of the task, this strategy may become less dominant and the priority of maintaining a *spatial margin* changes. Instead of acting to maintain the margin¸ the priority appears to be to maintain the straightest possible walking path, even if that means reducing the size of the protective zone.

The fact that the end-goal appears to act to maintain a straight walking path supports the principles of navigation proposed by Fajen and Warren (2003). The authors argued that the decision to go to the left or the right when circumventing obstacles is based on minimizing the deviations needed to the path trajectory (Fajen & Warren, 2003; Warren, 2006). Although obstacles push an individual off the straight walking trajectory, the attraction of the goal quickly pulls them back so that a walker can reach his or her goal by walking the straightest path possible. Patla and colleagues (2004) also observed that when participants are free to choose their path through a cluttered terrain, they select paths that reduce its total length. With respect to the current study, the desire to minimize deviation to the path trajectory likely overpowered the need to equalize the *spatial margin*: individuals were more willing to reduce the size of the margin and rotate their shoulders. Producing a shoulder rotation and maintaining a straight path was likely a preferred strategy in the current study because shoulder rotations during locomotion pose little, if any, threat to stability for a YA population. Future studies should consider investigating whether this strategy holds true in an OA population or for individuals who experience greater instability.

In general, participants rotated their shoulders more frequently as the second aperture was shifted farther from midline. However, it is important to note that post-hoc analyses demonstrated different trends across the three aperture sizes. The largest aperture size (1.7x SW) appeared to drive this effect, as the frequency of rotation increased from 15% of the trials for 25cm shifts to 60% for 75cm shifts. This result is much different than the 0% of rotations reported for this aperture size during single aperture crossing (Hackney et al., 2013) and highlights the role that path redirection (i.e., misaligned apertures) plays on crossing behaviour. Not surprisingly (and not included in the statistical analysis) rotations were produced for 100%

of the trials when the aperture was 0.9x SW, regardless of the size of the shift. This ceiling effect occurred because the aperture width was always smaller than the width of the shoulders and a rotation was therefore always necessary to successfully pass through the space. Interestingly 1.3x SW did not follow the trend to increase the *frequency of rotation* as the second aperture moved away from midline. Instead, there was a trend for the frequency to decrease as the shift increased (58% at 25cm shifts to 40% for 75cm shifts). Since aperture 1.3x SW represents the typical threshold between passable and impassable apertures, it is possible that individuals had more difficulty perceiving whether the aperture afforded passage because of its shift off of midline and the fact that it was not aligned with the body. An exact explanation for such a trend is out of the scope of this study: future work should examine perceptual judgements of the passability of apertures when they are off-set from midline in an attempt to understand whether the perceived *critical point* (division between passable and impassable apertures) is altered for misaligned apertures.

It is also worth noting that the amount of shoulder rotation produced at the second aperture was influenced by whether or not a shoulder rotation was required at the first aperture. Specifically, a shoulder rotation at aperture one led to greater rotations at aperture two compared to trials where the first aperture did not elicit a rotation. There are two possible explanations for why this effect may have occurred: (1) an altered, or different perceptual scaling between the two paths, or (2) a carry-over effect from the initial rotation. First, a number of studies have demonstrated that perceptual judgements about the size of an environment are influenced by both the perceived bioenergetics cost associated with the task and the individual's current performance (Proffitt & Linkenauger, 2013). For example, the distance of a steep hill is judged as greater than the same distance on flat ground (Stefanucci, Proffitt, Banton & Epstein, 2005), hills are judged as steeper when wearing a heavy backpack compared to judgements made without the bag (Bhala & Proffitt, 1999) and the distance to a target is judged as longer when throwing a heavy ball compared to a light one (Witt, Proffitt & Epstein, 2004). Furthermore, a bullseye is judged as larger when the archer is shooting well compared to when performance is poor (Lee, Lee, Carello & Turvey, 2012) and a passageway is judged as smaller when holding wide objects (Stefanucci & Geuss, 2009). In all of these circumstances, the environment was perceived differently, despite the fact that nothing was actually physically different about it. Therefore, the affordance of the environment likely changed because the perceived challenge or the perceived purpose changed. Perhaps something similar occurred in the current study whereby the path requiring three rotations was perceived as different from the path requiring only one. It has been suggested that based on the purpose of a task, individuals will turn themselves into walkers, throwers, graspers and so on, and in doing so, will transform the environment into the appropriate action-specifying units (Proffitt & Linkenauger, 2013). In the current study, participants may have perceived themselves as "turners" in the scenario where the first aperture required a rotation because the path consisted of apertures that all required rotations and as such, the environment was specified specifically for turning. On the other hand, when the first aperture was wide enough for straight walking, individuals may have become "navigators" and the environment may have been slightly modified in order to be specified for navigating.

An additional explanation as to why behaviour at aperture one influences behaviour for aperture two based on what action modifications are required for the first aperture may be due to the rotation itself. In all conditions, the direction of rotation at the second aperture always occurred such that the front of the body faced midline: if the aperture was located on the left side of midline, participants rotated with the left shoulder leading. On trials where the first aperture required a rotation, participants rotated away from midline at the first aperture in order to maintain a rotation toward midline for the second aperture. Due to the proximity of the apertures relative to one another, this means that participants essentially rotated from one direction to the other direction (they moved from a 45° rightward rotation to a 45° leftward rotation, almost 90° in total) without settling into a normal walking position in between the two apertures. This was not needed for trials that did not require a rotation at the first aperture, as individuals approached the second aperture in a neutral state, before producing an appropriate rotation (the moved from 0° rotation to 45°). Perhaps when individuals must swing the shoulders from one direction to the other, the movement becomes less accurate and the momentum of the swing leads to larger second rotations. Future studies should examine shoulder rotations from multiple starting positions in order to decipher whether the larger second rotations were indeed a result of the first rotation.

5.6 Conclusion

Overall the results of the current study demonstrate that aperture crossing through multiple, misaligned apertures appears to be guided by the attraction of the end-goal rather than an attraction to the center of the aperture(s). Individuals prefer to reduce the size of their spatial margin and rotate the shoulders rather than cross through the center of the aperture and equalize the *spatial margin* of the two shoulders. This strategy is likely used in an attempt to maintain the straightest possible walking path to the end-goal.

- Chapter 6 -

GENERAL DISCUSSION

6.1 Summary and Future Directions

As we move from place to place throughout our daily lives, we often encounter obstacles along the travel path that need to be avoided in order to reach our destination without injury. One such example is having to pass through narrow spaces, such as a partially blocked doorway or two closely parked vehicles. The ability to walk through apertures safety requires individuals to identify whether or not the aperture affords passage and to adjust their actions accordingly. Affordances, as described by Gibson (1979), are the possibilities for action available to an observer and reflect the fit between the size of the environment and the size of the individual. More recent work suggests that this body-environment relationship should also include the demand of the task as a contributing factor to the determination of affordances; as its demand will determine the action-specifying units (i.e., the *perceptual ruler*) an environment should be scaled to (Proffitt, 2013).

Previous literature has suggested that the affordance of aperture crossing is specified by the perceptual ruler associated with shoulder width. In particular, narrow spaces that are larger than 1.3x SW (i.e., the *critical point)* afford passage, while apertures smaller than this ratio do not (Warren & Whang, 1987). Recently, research has revealed that OA have a much larger *critical point* compared to YA despite similarities in shoulder size and that this larger *critical point* may be related to stability (Hackney & Cinelli, 2011). These results elude to the idea that body size alone may be insufficient for describing how affordances are determined and suggest that additional factors, such as alterations to the characteristics of the individual or the environment, are also considered by the perception-action system when determining the affordance of apertures.

Determining the factors that contribute to the identification of affordances is necessary for safe travel especially when one considers the variety of daily situations in which individuals may encounter a narrow space. Therefore, the general purpose of this thesis was to expand upon the current understanding of how the body-environment relationship influences aperture crossing behaviours. A series of studies were conducted with the broad focus of determining how different manipulations of this relationship influence the strategies used for safely passing through apertures. Specifically, this dissertation examined how altering characteristics of the individual (person-plus-object and postural threat) and characteristics of the environment (type of obstacles being crossed and multiple, misaligned apertures) affects avoidance behaviours.

Studies one through three employed similar methodologies in an attempt to provide the most direct comparison of the effects of each of the experimental manipulations. Following previous literature (Hackney & Cinelli, 2011; 2013b; Warren & Whang, 1987; Wilmut & Barnett, 2010), a narrow space was presented in the middle of the walking path, half way to a visible end-goal. The width of the space was randomly presented and varied from sizes that were smaller than the participant’s shoulder width to spaces almost double this size.

The final experiment in this series of studies expanded beyond the single aperture crossing technique to examine the manner in which individuals pass through multiple apertures. In this study, participants walked along a path toward an end-goal and passed through three separate apertures that varied in size and position relative to the midline of the path. This experiment focused on the action strategies employed when passing through the second aperture and the effects that shift and prior aperture crossing requirements had on this behaviour.

For all of the experiments, participants were instructed to walk to the end-goal and pass through the aperture without colliding with obstacles that created it. Aperture crossing behaviour was monitored by examining how often a shoulder rotation occurred *(frequency of rotation*), how large this rotation was at TOC *(magnitude of rotation*), and the distance from the aperture where these rotations were initiated *(onset of rotation)*. In studies one through three, these variables were used to identify the aperture width that represented the division between passable and impassable spaces (*critical point*). Furthermore, the average *approach velocity* and *trunk sway* observed as an individual approached the apertures were also considered. Additionally, the amount of space that an individual maintained between the shoulders and the outer-most edge of the obstacle at TOC (*spatial margin*) during the avoidance trials and the speed at which they crossed the aperture *(velocity at TOC)* were analyzed. These four variables were included in the analysis because they reflect the overarching architecture of the behaviour leading up and passing through the aperture. Lastly, in study four, the position of the M-L COM at the TOC of the middle aperture was also examined in order to determine whether participants aimed to maintain the straightest possible path trajectory when passing through apertures that were not aligned with the end-goal.

6.1.1 *Person-Plus-Object System (Study One)*

The first of the series of studies examined the challenges associated with carrying objects through narrow spaces. Specifically, study one evaluated how a person-plus-object system influences the perception-action relationship and the subsequent passability of apertures. Body size was altered by having participants carry a wide serving tray while walking through various-sized apertures. The aperture sizes were scaled to either the width of the participants' shoulders or the size of the tray, depending on whether the participants were instructed to walk while carrying a tray or whether they were completing the baseline condition (i.e., normal aperture crossing). Since the literature suggests that individuals can quickly rescale perceptual judgements to account for increases in body size (Franchak et al., 2010; Stefanucci & Guess, 2009; Wagman & Taylor, 2006) and that perceptual judgements about the passability of apertures match the actions made at the TOC (Franchak & Adolph, 2007; Hackney & Cinelli, 2013a), it was believed that individuals would quickly adapt to the tray by maintaining a constant *critical point* regardless of whether the tray was carried.

The findings suggest that objects being carried are treated as extensions of the body and behaviour is quickly adapted to accommodate for the new person-plus-object width. This was evident by the fact that the *critical point* remained the same as that of normal walking when the environment was scaled to the new person-plus-object width: impassable apertures were considered those 1.3x object width or smaller. Even though adaptation to walking with a tray varied across participants, all individuals were able to incorporate the size of the tray with their body size when selecting an appropriate aperture crossing behaviour by the end of the experimental trials. The results from the first study contribute two major findings to the aperture crossing literature:

1) *The perceptual ruler used to specify the environment for aperture crossing can be successfully modified to account for objects that increase the size of the body.*

2) *Individuals adapt this perceptual ruler at different rates.*

Future work should examine why people appear to adapt at these different rates. For example, participants who initially increased their *critical point* when carrying the tray may be less confident in their decision about the passability of the aperture and as such, choose to rotate their shoulders at larger relative aperture widths to ensure safety. Furthermore, future research should examine whether OA are also able to scale the *critical point* to the person-plus-object width as quickly and as accurately as their younger counterparts. Determining whether OA are affected by carrying or using objects that extend the width of the body, such as mobility aids, could help determine whether the design of spaces frequently navigated by OA should consider any of these altered behaviours when attempting to improve the safety and ease of locomotion through such spaces.

6.1.2 Postural Threat (Study Two)

Knowing that the perceptual-motor system can quickly account for changes in body size, the second study investigated whether it can also adapt to changing levels of postural threat. Postural threat was manipulated by increasing the risk associated with losing balance by having participants walk along a narrow path or an elevated/narrow path while passing through an aperture. Aperture crossing behaviours were observed under these experimental conditions and compared to that of normal, ground-level walking. Since previous research has demonstrated a correlation between instability and an increased *critical point* (Hackney & Cinelli, 2013a) and that postural threat decreases stability during walking (Brown et al., 2002; McKenzie & Brown, 2004; Schrager et al., 2008), it was believed that the passability of apertures would be altered under conditions of postural threat. Specifically, it was anticipated that individuals would employ a more cautious approach by reducing walking speed and rotating the shoulders for larger relative aperture widths for both experimental conditions but that these observed effects would be greatest on the elevated/narrow path.

The findings revealed that the passability of apertures is indeed altered during conditions of increased postural threat. However, this effect was only observed in the elevated/narrow path condition. Individuals had greater *trunk sway,* walked slower, rotated their shoulders for larger relative aperture widths, and maintained a larger *critical point* when postural threat was high compared to normal walking. All of these outcomes were considered to have a moderate to high effect sizes. Despite a decrease in *walking speed* and an increase in *trunk sway* in the narrow path condition, the *critical point* remained similar to that of normal, ground walking. Therefore, the results from the second study contribute two major findings to the aperture crossing literature:

(1) The affordance of aperture crossing considers postural threat when determining the passability of apertures and that the critical point, walking speed, and trunk sway are altered under such conditions.

(2) In a YA population, the passability of apertures may only be affected once a certain level of postural threat has been reached, despite the presence of altered gait characteristics.

Since the passability of apertures was only affected in the elevated/narrow condition, future research should investigate whether there is indeed a threshold associated with changes in *trunk sway* and/or *walking speed* and changes to the *critical point* and whether this threshold can be achieved at ground level in a YA population. Furthermore, the results from this second study support the idea that differences in dynamic stability can help explain why OA have a larger *critical point* compared to their younger counterparts (Hackney & Cinelli, 2011). A potential future direction therefore, is to examine whether improving the dynamic stability of an OA can reduce the size of the *critical point* to that of a YA population.

6.1.3 Human Apertures (Study Three)

The third experiment in the series of studies focused on how changing the characteristic of the environmental objects influences the strategies used to walk through them. Specifically, the third study examined how the passability of apertures is altered when walking through similar sized gaps that were created by either human or pole obstacles. It was anticipated that individuals would maintain a larger *critical point* when passing through two human obstacles compared to two pole obstacles in order to account for the social factors involved with avoiding the invasion of another individual's personal space.

The results from this third study revealed that when the obstacles were human, individuals rotated their shoulders more frequently at larger apertures, as evident by a larger *critical point* (1.7 vs 1.3 for poles; moderate-high effect size), initiated shoulder rotations earlier, rotated to a larger degree, maintained a wider *spatial margin*, and walked slower when approaching and passing through the human obstacles compared to pole obstacles. Furthermore, correlational analyses revealed that the amount of change between an individual's *critical point* for the poles and the *critical point* for the human obstacles was related to both social risk-taking scores and changes in *walking speed*. Therefore, the third study provides the following major finding to the aperture crossing literature:

1) *The perceptual ruler used to determine the appropriate aperture crossing behaviour when crossing human obstacles is influenced by social context associated with human obstacles.*

Since social factors appear to influence how the affordance of an aperture is identified, future research should focus on identifying which social factors and the extent that such factors contribute to altering the passability of apertures. For example, since the current study used female confederates only, it would be worth examining behaviours for crossing between two males or a male/female combination and establishing whether gender differences arise. Lastly, future research should examine aperture crossing under a variety of social situations experienced on a daily basis such as when the confederates are known to the participants or when the confederates are engaging in a conversation. The results from the current study and the experiments stemming from it will help provide the necessary ground work for determining the role that social context plays with respect to aperture crossing behaviours and how different social scenarios may influence how individuals navigate through cluttered environments.

6.1.4 Multiple, Misaligned Apertures (Study Four)

Lastly, the final experiment expanded the examination of aperture crossing behaviours by including multiple apertures in order to begin to understand how individuals navigate scenarios similar to stationary crowds. Specifically, the fourth study set out to determine whether individuals choose paths based on an attraction to the end-goal (as suggested by the behavioural dynamics model; Fajen & Warren, 2003; Warren, 2006) or an attraction to the center of the aperture (as suggested by the equalization theory; Cinelli et al., 2006). In order to test this, participants walked through three separate apertures en route to an end-goal. The apertures varied in size and the middle aperture was shifted away from the midline of the path. The purpose of the shift was to ensure that participants needed to deviate away from the straight walking path in order to pass through the aperture and ensure that he/she was not aligned with the end-goal throughout the entire trial. This way, if participants were attracted to the center of each aperture, he/she would adjust their walking trajectory for the second aperture in order to pass through its center by deviating further away from the midline of the path and equalizing the size of the *spatial margin* at TOC. However, if behaviour is guided only by the location of the end-goal, participants would likely aim to walk the straightest possible path by deviating less from the midline and pass through the aperture closer to the obstacle nearest midline (reducing the *spatial margin*). It was anticipated that behaviour would be similar to that predicted from an end-goal attraction point, whereby the desire to maintain the straightest possible walking path would override the desire to walk through the center of the aperture.

A comparison of the M-L position of the COM at TOC (*distance from* center) and the *spatial margin* for the shoulder closest to midline revealed a significant and powerful effect of shift. Specifically, individuals walked farther from the center of the aperture and decreased the size of the *spatial margin* as the shift size increased. Furthermore, a significant and moderate effect was observed for *frequency of rotations* such that individuals rotated their shoulders more often at the middle aperture as the shift increased. The results of study four contribute two major findings to the aperture crossing literature:

1) *The attraction of the end-goal and a desire to maintain the straightest possible walking path guides path trajectory through multiple apertures.*

2) *Unlike single aperture crossing where individuals act to maintain an equally-sized spatial margin on either side of the shoulders, individuals choose to reduce the size of the margin for one shoulder and rotate the shoulders during multiple, misaligned aperture crossing even if the aperture is such a size where a rotation is not normally required.*

Crowded environments such as those encountered when rushing through a busy airport often involve navigating through multiple people with (and without) carrying luggage. These scenarios are frequently associated with increased anxiety or stress. Using the results of the current study as a baseline comparison, future attempts to understand the navigation of multiple aperture environments should include conditions of increased anxiety in order to establish a detailed understanding of these strategies.

In general, this thesis offers a more comprehensive understanding of how YA walk through apertures when alterations to their body size or balance are imposed, as well as during situations where the characteristics of the environment have been altered. Based on the knowledge gained from the studies' results, it is recommended that future research examine different populations (e.g., OA fallers) in order to test the robustness of the theories put forward.

6.2 Implications

6.2.1 Theory of Affordances and the Affordance of Aperture Crossing

As stated many times throughout this dissertation, Gibson (1979) argued that the actions that an individual performs within a given environment are the product of the fit between the environment and the individual and it is this body-environment relationship that determines the possible actions available to an individual. A review of the literature suggests that for aperture crossing, the property of the individual most relevant to the determining the actions necessary to pass through an aperture is considered to be the widest horizontal dimension of the body (i.e., the shoulders; Higuchi et al., 2012; Warren & Whang, 1987; Wilmut & Barnett, 2010). Recent work has recognized the role that action capabilities and limitations to movement play on determining possibilities for action with specific focus on steering, braking and intercepting (Fajen, 2007 & 2013; Fajen, Diaz & Cramer, 2011; Fajen, Matthis, 2011). The results of studies one through three presented in this thesis support this idea and demonstrate that body size alone is not the only factor(s) that is used by the perceptual-motor system when specifically identifying the affordance of aperture crossing. This is evident by the fact that the passability of apertures changes under challenging conditions despite both the size of the body and the size of the environment remaining unchanged. As outlined in the summary section above (Section 6.1), the results of the experimental manipulations in studies one through three demonstrate that: 1) although the *critical point* remains 1.3 for a person-plus-object system, the perceptual-motor system adapts to consider the widest dimension of this person-plus-object system (i.e., the tray is embodied and considered an extension of the body) and that this adaptation rate varies across individuals, (2) when postural threat is high, the *critical point* increases to 1.5x SW, which is likely a strategy to account for the increased M-L *trunk sway*, and (3) the *critical point* increases to 1.7x SW when walking through apertures created by human obstacles, suggesting that the passability of apertures is also influenced by the type of object being crossed and not simply the size of the gap.

A secondary outcome of this dissertation was the ability to analyze the robustness of the *critical point* for normal, ground-level walking. With a group of ten male participants, Warren and Whang (1987) first reported that individuals will rotate their shoulders for apertures smaller than 1.3x SW and will walk straight through gaps larger than this ratio. Each of the studies presented in this dissertation included a normal aperture crossing task and as such, a combined total of seventy participants (37 females and 33 males) completed a normal aperture crossing scenario. This data, combined with data collected from two of my previous experiments (Hackney & Cinelli 2013; Hackney et al., 2013b) allowed for a dataset of ninety-two YA participants. On average, the group *critical point* was calculated to be 1.3x SW (±0.07) and there was no significant differences between male and female participants (Figure 6.1a). Furthermore, a distribution of the individual *critical points* (Figure 6.1b) revealed a normal distribution pattern and that 76% of the participants (70 of 92 participants) had a *critical point* of 1.3. Not only does this confirm that the *critical point* of 1.3x SW for normal aperture crossing is reproducible but it also suggests that any observed changes to the value of the *critical point* for future experimental manipulations can be attributed to the manipulation itself and not simply to differences in the baseline behaviour of the groups being tested.

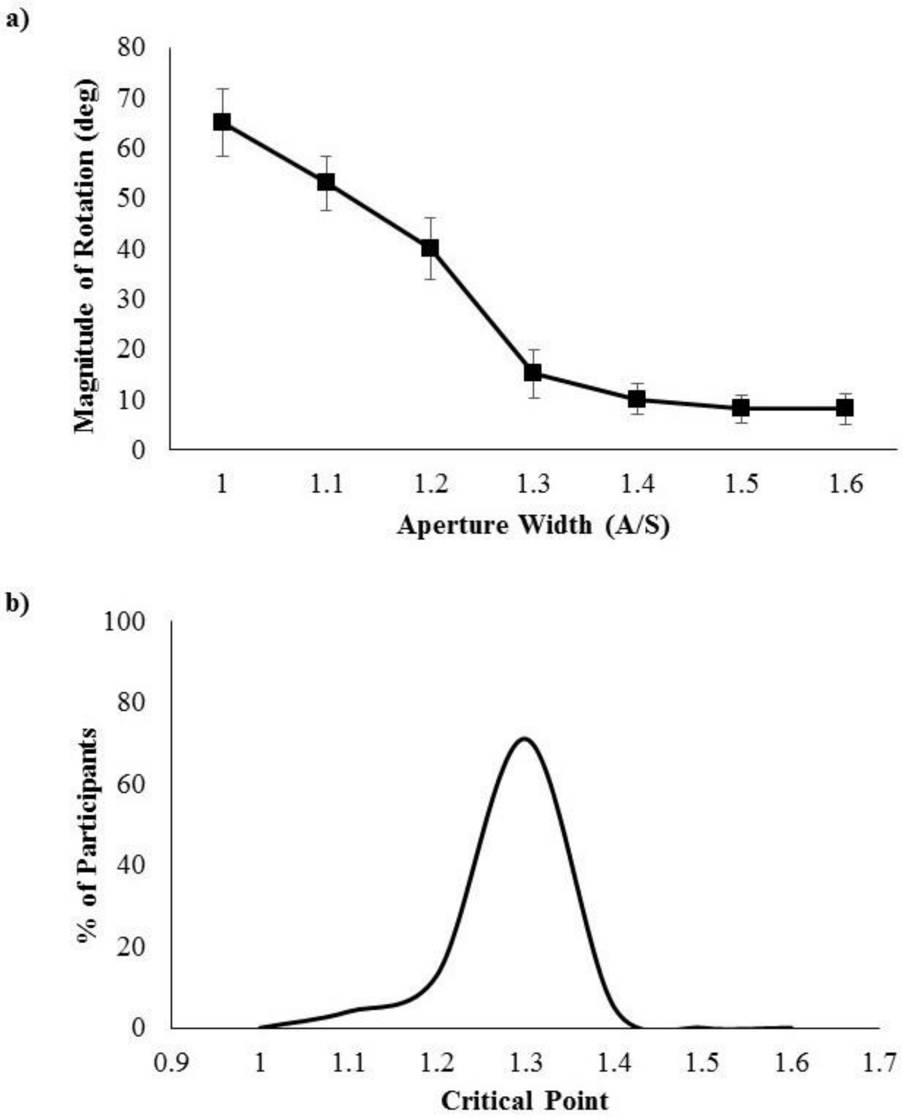

Figure 6.1 – Data collapsed across the baseline conditions (normal, ground-level aperture crossing; N = 92) displays **a)** the group *frequency of rotation* for each aperture width and **b)** the distribution of individual *critical point* values.

In addition to the distribution of individual *critical point* values for the normal, ground-level aperture crossing, a similar distribution for each experimental manipulation examined in this dissertation has been plotted in Figure 6.2. When compared to normal aperture crossing, this analysis demonstrates that: 1) narrow path walking follows the same distribution pattern, confirming that the passability of apertures remains unchanged when YA walk on a 20cm wide path; 2) although the average *critical point* for tray-carrying was similar to baseline, the distribution is platykurtic compared to normal aperture crossing (i.e., more variability) which is likely driven by the subset of participants whose *critical point* fluctuated throughout the length of the experiment; and 3) the distribution for both the elevated-walking and human obstacles condition are skewed rightward, such that the average *critical point* increases compared to baseline. Not only do these two distributions confirm that the passability of apertures is affected by postural threat and animate obstacles, but it also confirms that the *critical point* does not simply emerge as the median value of the range of aperture sizes being presented. The fact that the passability of apertures appears to be most affected by postural threat and the characteristics of the objects not only has implications for the understanding of aperture crossing in OA populations who are inherently less stable, but it may also establish the baseline information necessary for providing suggestions for the design of spaces (discussed more thoroughly in the following section).

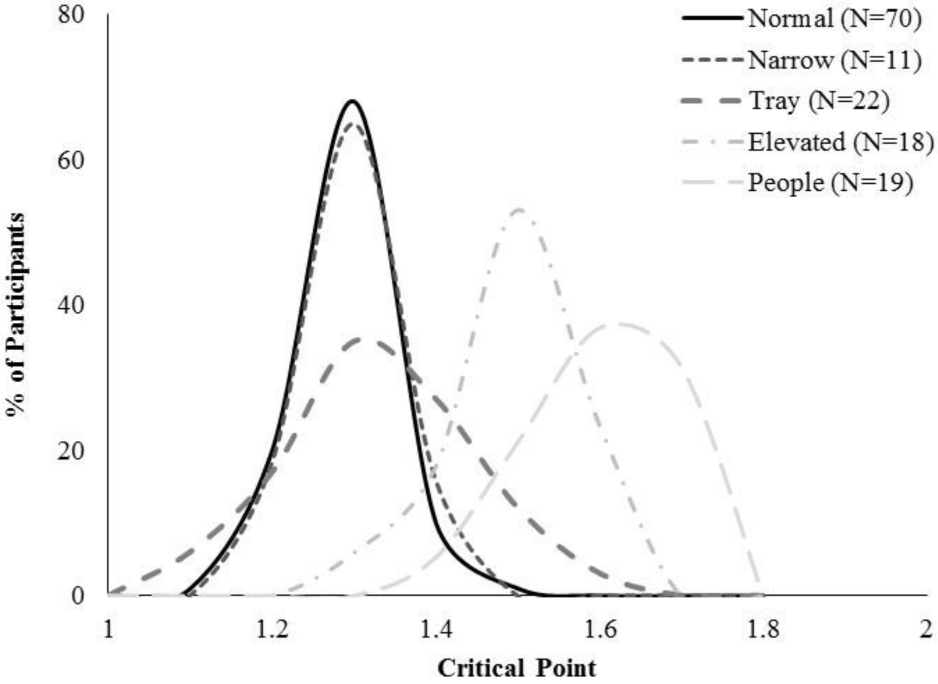

Figure 6.2 – A distribution of individual *critical points* for each of the samples collected from studies one through three.

Lastly, the results of study four support the idea that task demand plays an important role in the identification of affordances. Proffitt and Linkenauger (2013) extended the notion of a body-environment relationship to include a third factor, the demand of the task, and argued the environment is scaled to the appropriate action-specifying units based on the perceived purpose of the task. This means that a given environment can be specified in different ways depending on how the observer intends to use it. For example, a chair may be specified differently based on whether the task demands that it be used it as a chair to sit on or as a stool to stand on. The majority of evidence to support this claim is focused on perceptual judgements and does not include an analysis of action. However, the results of study four provide action-related evidence to support this idea. Since individuals behaved differently at the second aperture based on the size of the first, individuals may have perceived the two tasks as having slightly different demands. In the scenario where the first aperture required a rotation, participants may have perceived themselves as “turners” because the path consisted of apertures that all required rotations and as such, the environment was specified for turning. On the other hand, when the first aperture was wide enough for straight walking, individuals may have become “navigators” and the environment may be slightly modified in order to be specified for navigating.

Overall, the findings from the series of studies presented in this dissertation support and extend the idea that affordances are determined based on a body-environment-demand relationship. With these results I propose that *person-plus-object size* be added to the body size portion of the conceptual model of affordances (Chapter 2), as individuals are able to account for changes in body width associated with carrying objects. I also propose that *aperture characteristics* be added to the environment-portion of this relationship (Chapter 4 and 5), as the affordance of aperture crossing is influenced by social factors associated with walking through human-obstacles and the location of the aperture relative to the goal, despite the fact that the body size and the aperture size remained unchanged. Furthermore, considering the results of my previous work (Hackney & Cinelli, 2011; 2013c; Hackney et al., 2015) and this dissertation, I support the idea that *abilities* are an important contributing factor to the identification of affordances (Fajen, 2013) and propose that the conceptual model of affordances should contain individual *abilities* as a fourth factor (Chapter 3), as the passability of an aperture can change based on the abilities of the individual. A visual representation of the proposed additions to the conceptual model of affordances is presented in Figure 6.3.

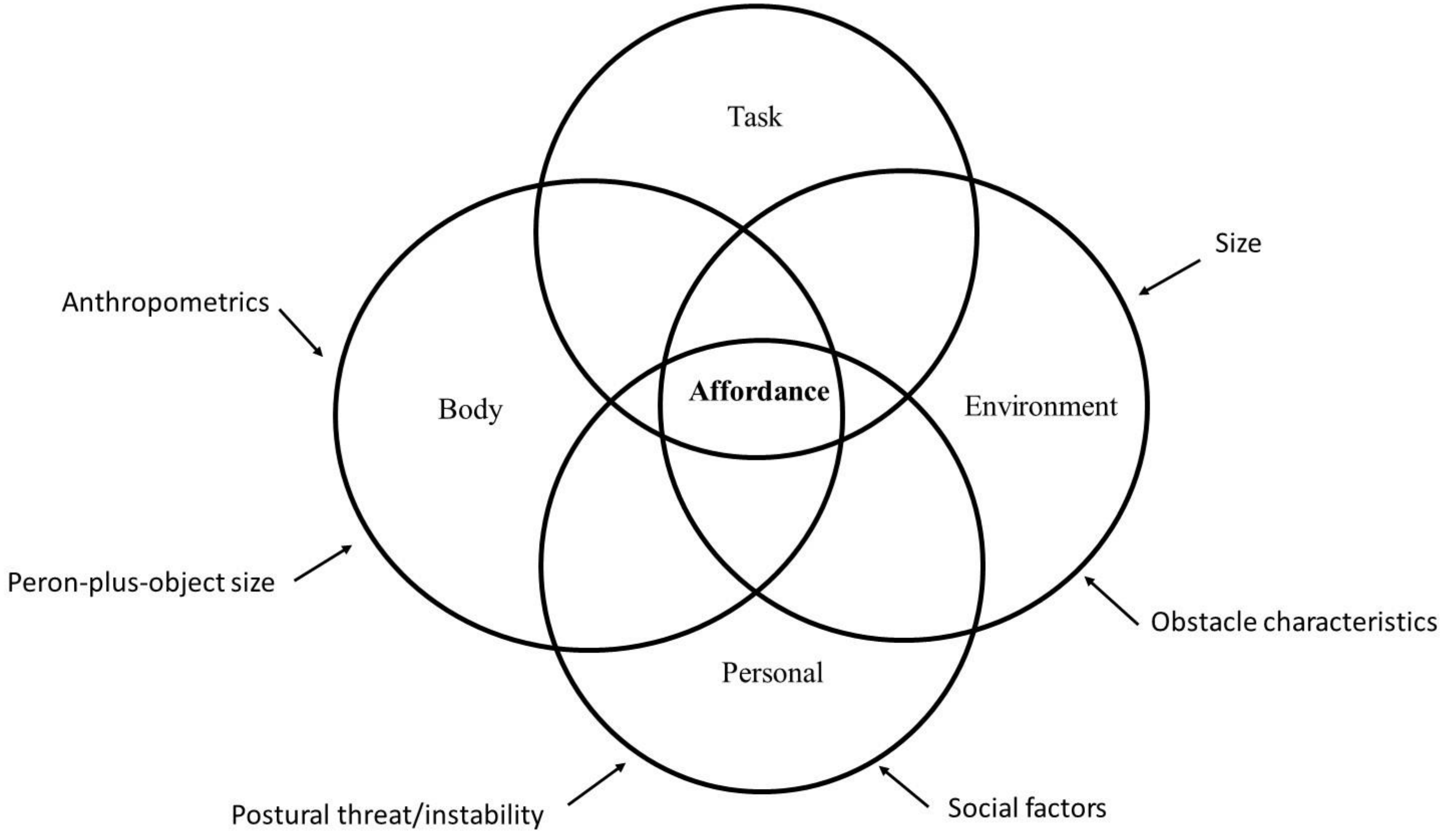

Figure 6.3 – A visual representation of the proposed additions to the conceptual model of the affordance of aperture crossing, as were manipulated in the dissertation.

If affordances do indeed emerge from the interaction of factors influencing the body, the environment and an individual’s action capabilities, then the proposed affordance model above is far from a complete account. The suggested additions outlined in the above figure (Figure 6.3) merely incorporate a subset of factors that were directly manipulated within this dissertation, however it would be naive to argue that these are the only important considerations. The diagram below (Figure 6.4) highlights some additional contributing factors that were not directly examined, but that are important to acknowledge, which may affect how individuals choose and guide their actions. Although the aperture crossing literature itself has yet to address many of these factors, a broader review of the literature can shed light on additional environmental, task and personal factors that should be considered.

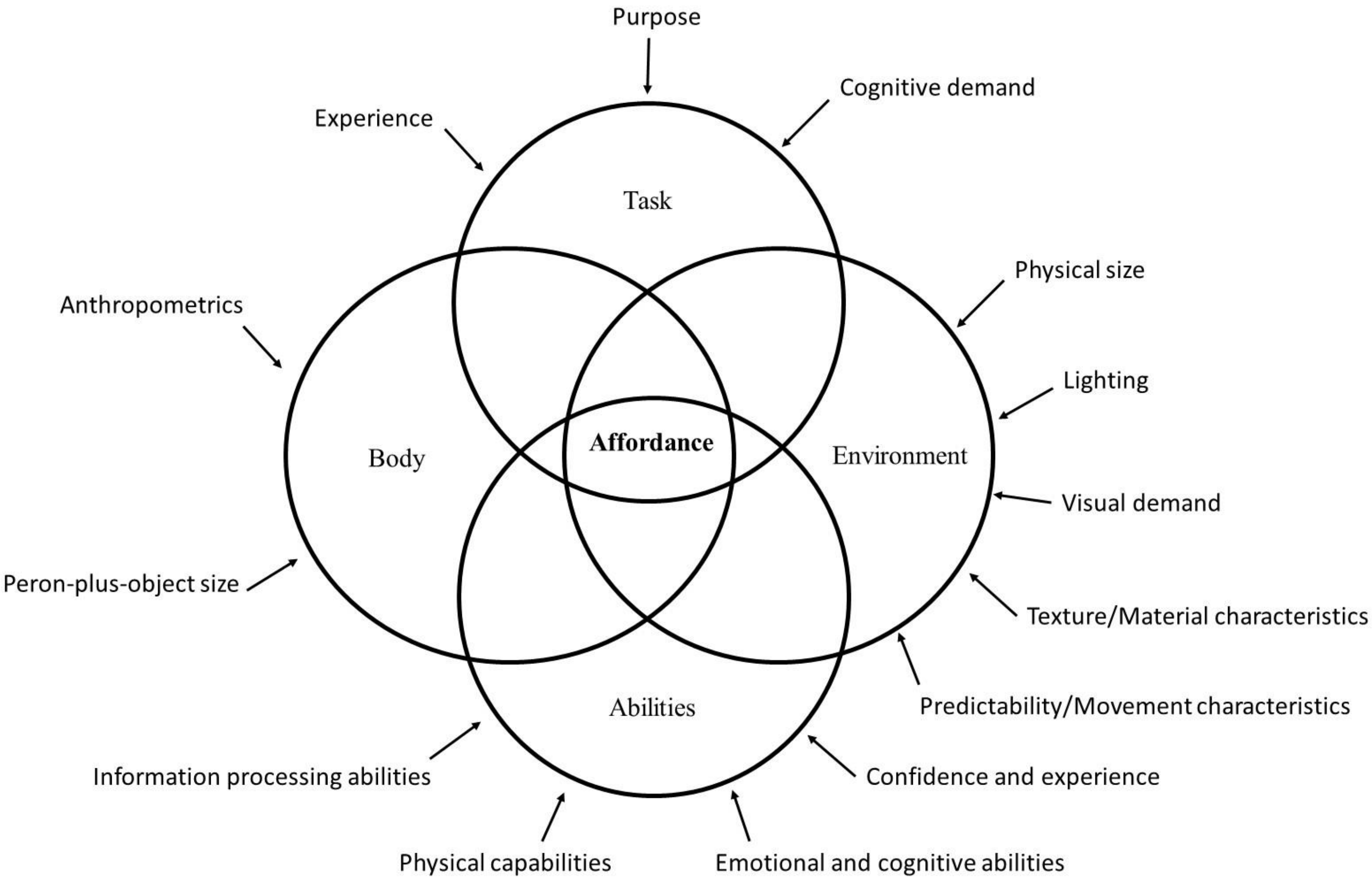

Figure 6.4 – A detailed diagram of the many possible influences to how individuals guide movement through space.

As was addressed previously in this section, physical size and human versus pole obstacles were both suggested as “environmental” factors that can influence the actions that are and are not deemed possible for an individual. Although not explicitly examined within the research studies presented, it is important to acknowledge the impact that other factors may have on action choices, such as the visual demand of the environment. Davenport and Potter (2004) argued that the details about an object are processed interactively with their background and that an object’s size is identified more accurately when presented in isolation or with a constant setting rather than within a busy, changing background. Additionally, steering accuracy and driving behaviour have been shown to decrease in environments with low luminance compared to scenes with high luminance, likely because the visual information obtained from the scene is less rich and may require additional time to process (Owens & Tyrell, 1999). Different colouring and textural layout of the background, as well as the presence (or absence) of peripheral objects in the space may have assisted with (or distracted from) the ability to accurately judge the size of the aperture(s). Since half of the studies presented in this dissertation were completed within a different laboratory than the others (Studies One and Four at Wilfrid Laurier University and Studies Two and Three at the University of Waterloo), it is possible that the visual demands of the two environments contributed to some of the differences observed in the results. Perhaps one environment provided visual information that would assist an individual in making decisions about an aperture size while the other delivered visual information that merely distracted from this decision. Studies that stem from the work presented in this dissertation should consider evaluating the perceptual judgements and action choices that result from different visually demanding environments to better distinguish how visual demand influences affordance perception.

Cognitive demands of the environment in which an individual is traversing also will likely have a large impact on how he/she performs. Obstacle clearance for example, is influenced by the attentional demand of the task where distractions or the need to divide attention negatively impacts performance. Even in a young adult population, obstacle avoidance performance decreases with increased level of difficulty (Sui, Catena, Chou, van Donkelaar & Woollacott, 2008; Weerdesteyn, Schillings, Van Galen, & Duysens, 2003). In addition to being included as an “environmental” factor, cognitive demand (with specific focus on cognitive abilities) should also be incorporated into the “personal” section. Research has demonstrated that individuals with a decreased capacity to attend to increased cognitive demand, such as individuals recovering from a traumatic brain injury (McFadyen et al., 2009) and older adults (Alexander, Ashton-Miller, Giodani, Guire & Schultz, 2005) show residual locomotor deficits during multi-tasking compared to their healthy counterparts. With respect to the studies presented in this dissertation, one should not discount the influence of a more cognitively challenging environment. This is especially true for the elevated path walking, where participants were required to make judgments about the passability of an aperture while also ensuring that they did not fall off the platform. It is possible that the cognitive demands of maintaining balance influenced affordance perception. Future work may consider evaluating whether the increased cognitive demand of a task can indeed alter the perceived affordances within a young adult population.

Experience can also influence actions that are chosen within a given environment. Research examining the effect of experience on behaviour has revealed that judgments of ability are more precise in experienced individuals compared to novices. For example, basketball players are more accurate at perceiving their maximum reach-with-jump ability than non-basketball players (Weast, Shockley & Riley, 2011) and football players leave smaller spatial margins when running through narrow spaces with shoulder pads on compared to non-football players (Higuchi, et.al., 2011). With respect to driving performance, the visual strategies of experienced drivers can be adapted to the complexity of the task, but the strategies of novice's are too inflexible to meet the changing cognitive demands (Crundall & Underwood, 1998). Even at a young age, research has observed that infants and toddlers will choose actions that reflect their level of experience: experienced crawlers or walkers will refuse to cross gaps that are too large but novice movers will attempt them (Adolph, 1997).

This dissertation demonstrated that the affordance of aperture crossing considers the person-plus-object system, postural threat, obstacle type (pole versus human obstacles) and type of aperture crossing (single versus multiple). How individuals choose what actions are and are not afforded likely depends on an even larger framework that requires further exploration.

6.2.2 Affordance Design

Designers and architects create places and objects that afford walking, sitting, using, etcetera. However, the standards that outline how such spaces and artifacts should be built are based on anthropometric standards or personal judgement (Panero & Zelnick, 1979; Norman, 1999). The purely anatomical nature of anthropometric standards indicates that there is a complete disregard for the functional interactions users have with the world (Diffrient, Tilley & Bardogjy, 1974; Maier, Fadel & Battisto, 2009). Basing architectural standards solely on anthropometric data becomes problematic when one considers the diversity of abilities within the population. For example as outlined by Warren (1995), the functional *critical point* associated with climbable stairs for an OA population may be different than the geometric one simply because of limitations in flexibility and strength. Since many of our daily interactions with the environment involve factors other than body size (such as stability, cultural norms of body space, strength, etc.), it is not surprising that the affordance literature has sparked discussion about a new affordance-based approach to architectural design that focuses on bringing functional factors into consideration (Maier & Fadel, 2009).

Similar to stair climbing, Warren (1995) advocated for the necessity of a task-specific affordance analysis when architects go about determining the minimum aperture width necessary for the design of narrow spaces. Instead of the current architectural standard of 21in/53cm, he proposed that the minimum standard following an affordance-based approach should be 25in/63cm, or roughly 1.3x the average SW in order to account for the natural body sway and spatial margins necessary for single, flat-ground aperture crossing (Warren, 1995). The major findings of studies one through three in this dissertation offer a more comprehensive task-specific analysis for the design of narrow spaces by providing additional recommendations for affordance-based standards of passage width. These specific recommendations are presented in Table 6.1.

Furthermore, the results of study four suggest that individuals behave differently when walking through single and multiple apertures. As such, these results highlight the need for the design of these spaces to reflect these differences. Although it is out of the scope of this thesis to provide exact recommendations for building spaces that include multiple narrow gaps, future work stemming from these findings may be able to provide such suggestions.

Table 6.1- Recommendations for ecological standards of passage width based on task-specific affordance analysis.

Task-specific use of space	Affordance-based Standard	π
*Ground-level, single aperture, pole obstacles (Warren & Whang, 1987)	25in / 63.5cm	1.3
*Ground-level, single aperture, pole obstacles, older adults (Hackney & Cinelli, 2011)	30in / 76cm	1.6
Ground-level, single aperture, pole obstacles, objects are being carried (Hackney, Cinelli, & Frank, 2014)	Based on the average size of the object being carried	1.3
Ground-level, narrow base/path, single aperture, pole obstacles (Hackney, Cinelli, Denomme, & Frank, 2015)	25in / 64cm	1.3
Elevated base/path or increased risk associated with failure, single aperture, pole obstacles (Hackney, Cinelli, Denomme, & Frank, 2015)	28.5in / 73cm	1.5
Ground-level, single aperture, human obstacles (Hackney, Cinelli, & Frank, 2015)	32.5in / 83cm	1.7

*Recommendations taken from the results of previous experiments not included in this thesis

The fact that the *critical point* changes when different factors of the body-environment relationship are altered highlights the importance of knowing the purpose or intended use of the space when designing spaces. For example, the spatial layout of a restaurant floor should consider the size of the person-plus-object system navigating through that space. Will the servers be navigating around inanimate objects such as tables or will animate obstacles, such as stationary or moving people also be a concern? How large are the plates and platters being delivered to tables? Can servers move from table to table comfortably without risking collisions with customers while carrying hot food or cold drinks?

6.3 Final Conclusions

Walking through narrow spaces requires that individuals identify whether the aperture affords safe passage. This thesis has reviewed the existing literature on the affordance of aperture crossing and extended the current understanding of how the body-environment relationship and alterations to it can modify the passability of these narrow spaces. A series of experiments were conducted, each which manipulated different aspects of the body-environment relationship and monitored the resulting effect on crossing behaviour. Despite the fact that the size of the body and the size of the aperture remains unchanged, the passability of apertures changes under conditions of postural threat, if the obstacles have human characteristics and based on the position of the aperture relative to the end-goal. These results suggest that the *perceptual rulers* used by the perceptual-motor system to scale the environment into action-specifying units must consider more than just the body size when identifying affordances but is able to adapt to changes to the body size. An example of this adaptation was observed when individuals carried wide objects, as the passability of an aperture was rescaled to consider the size of the person-plus-object width. With these results, I proposed that the conceptual model of affordances expand to include an individual's "abilities" as a fourth factor and add both the "person-plus-object size" in the body-aspect of the relationship and "aperture characteristics" to the environment-portion of the model. As a whole, this thesis demonstrates that the affordance of aperture crossing is not simply determined by the size of the shoulders but instead is adapted to encompass an array of factors experienced on a daily basis. It is my hope that the results of this dissertation provide the groundwork for future studies examining older or special populations and provide valuable information for the affordance-based design of spaces that contain narrow spaces.

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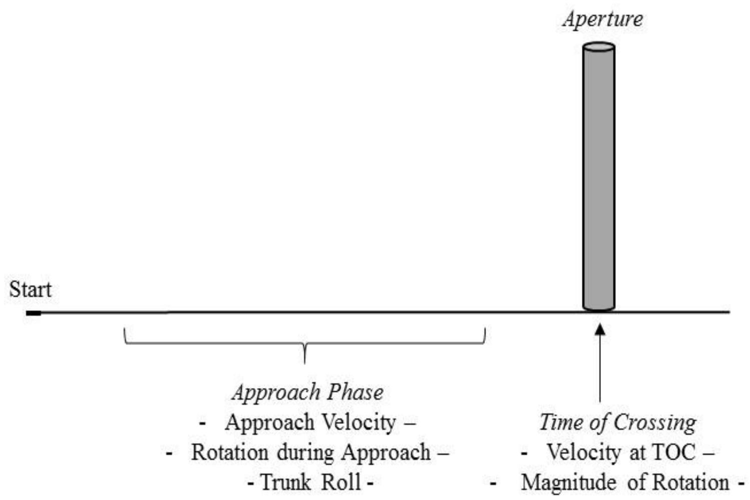
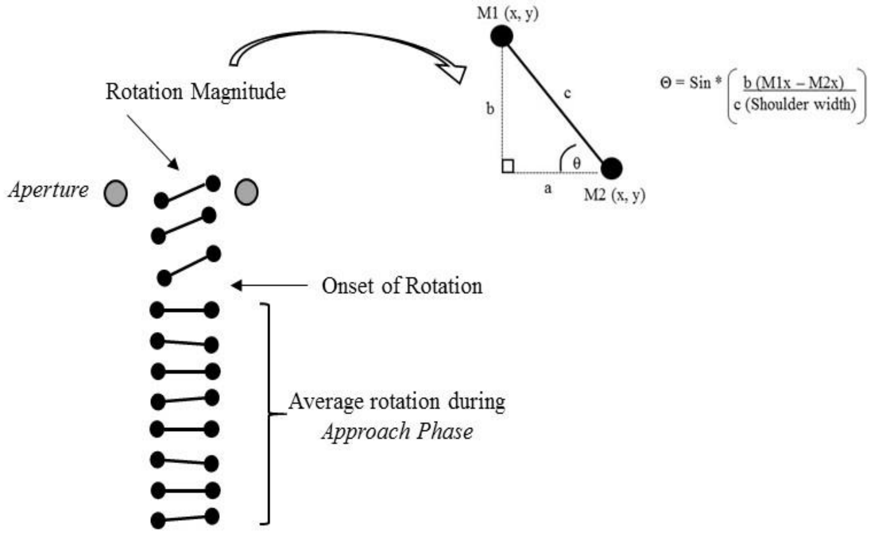
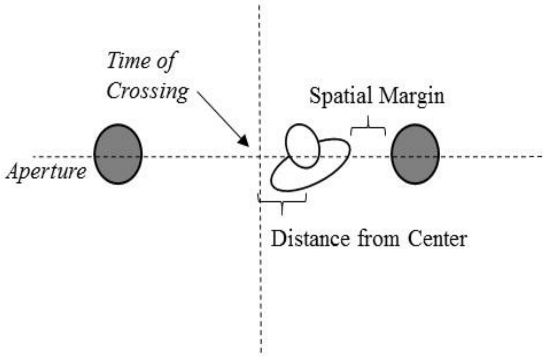
APPENDIX A – Dependent Variables


Aperture
Start
Approach Phase
- Approach Velocity –
- Rotation during Approach –
- Trunk Roll -
Time of Crossing
- Velocity at TOC –
- Magnitude of Rotation -


M1 (x, y)
Rotation Magnitude
b
c
θ
a
M2 (x, y)
$\Theta = \text{Sin}^{*}\left(\frac{b\ (M1x - M2x)}{c\ (\text{Shoulder width})}\right)$
Aperture
Onset of Rotation
Average rotation during
Approach Phase


Time of
Crossing
Spatial Margin
Aperture
Distance from Center

APPENDIX B – Screening Questionnaire

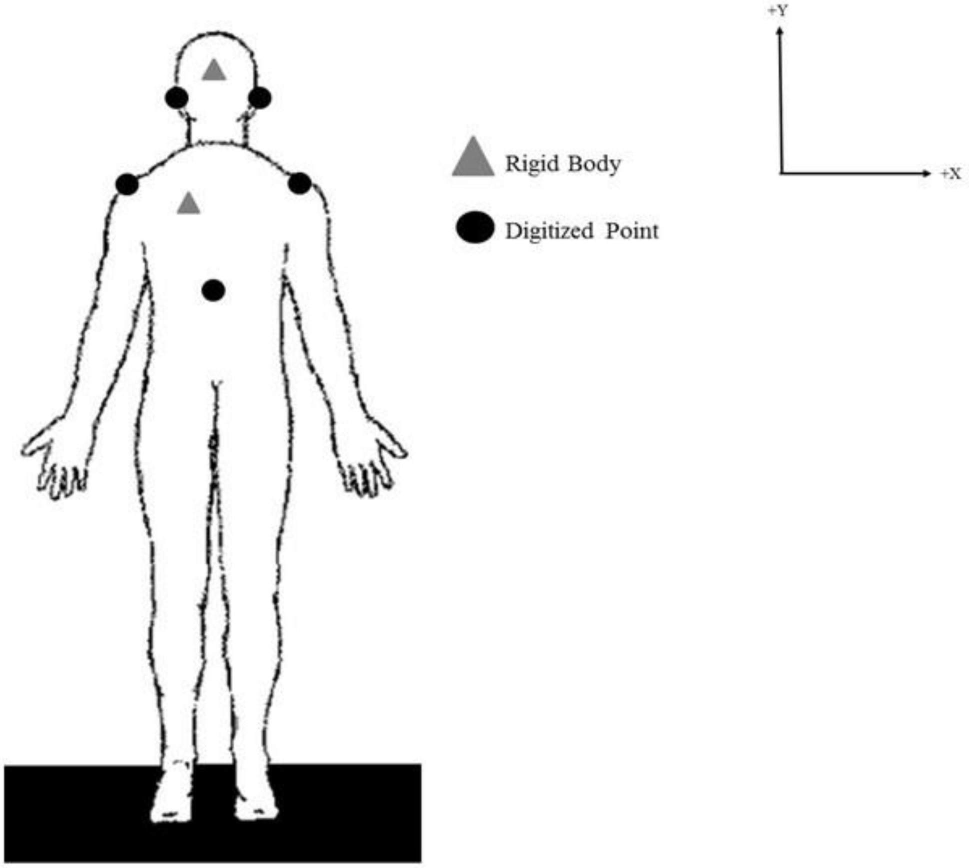
Year of Birth ___________ Gender: Male / Female

1. Do you wear glasses/contacts? YES / NO
2. Do you have a visual impairment? YES/NO

   If yes… what type of visual impairment do you have (i.e. macular degeneration, cataracts, etc.)? ________________________
3. Have you been diagnosed with severe balance impairment? YES / NO
4. Are you currently taking any medication that may affect your balance? YES / NO
5. Have you had ankle, knee or hip injury within the last year? YES/NO
6. Have you had a shoulder injury/surgery within the last year? YES/NO
7. Are you a varsity athlete or do you train with a competitive sports team? YES/NO

   If yes… what sport do you play? ____________________
8. How many hours a week are you physically active? __________
9. Do you have trouble maintaining balance during everyday activities? YES/NO
10. Have you experienced or been diagnosed with any of the following? Please check all boxes that apply.
    - ☐ Multiple Sclerosis
    - ☐ Attention Deficit Disorder/Attention Deficit Hyperactive Disorder
    - ☐ Autism
    - ☐ Vestibular dysfunction/disorder (i.e. vertigo)
    - ☐ Sensory processing disorder
    - ☐ Hearing impairment
    - ☐ Visual impairment
    - ☐ Osteoporosis
    - ☐ Traumatic brain injury (i.e. concussion)
    - ☐ Severe knee, hip, ankle or back pain

APPENDIX C – IRED Marker Setup & COM Calculations



A-P COM Calculation

= (left shoulder_y * 0.25) + (T10_y * 0.50) + (right shoulder_y * 0.25)

M-L COM Calculation

= (left shoulder_x * 0.25) + (T10_x * 0.50) + (right shoulder_x * 0.25)

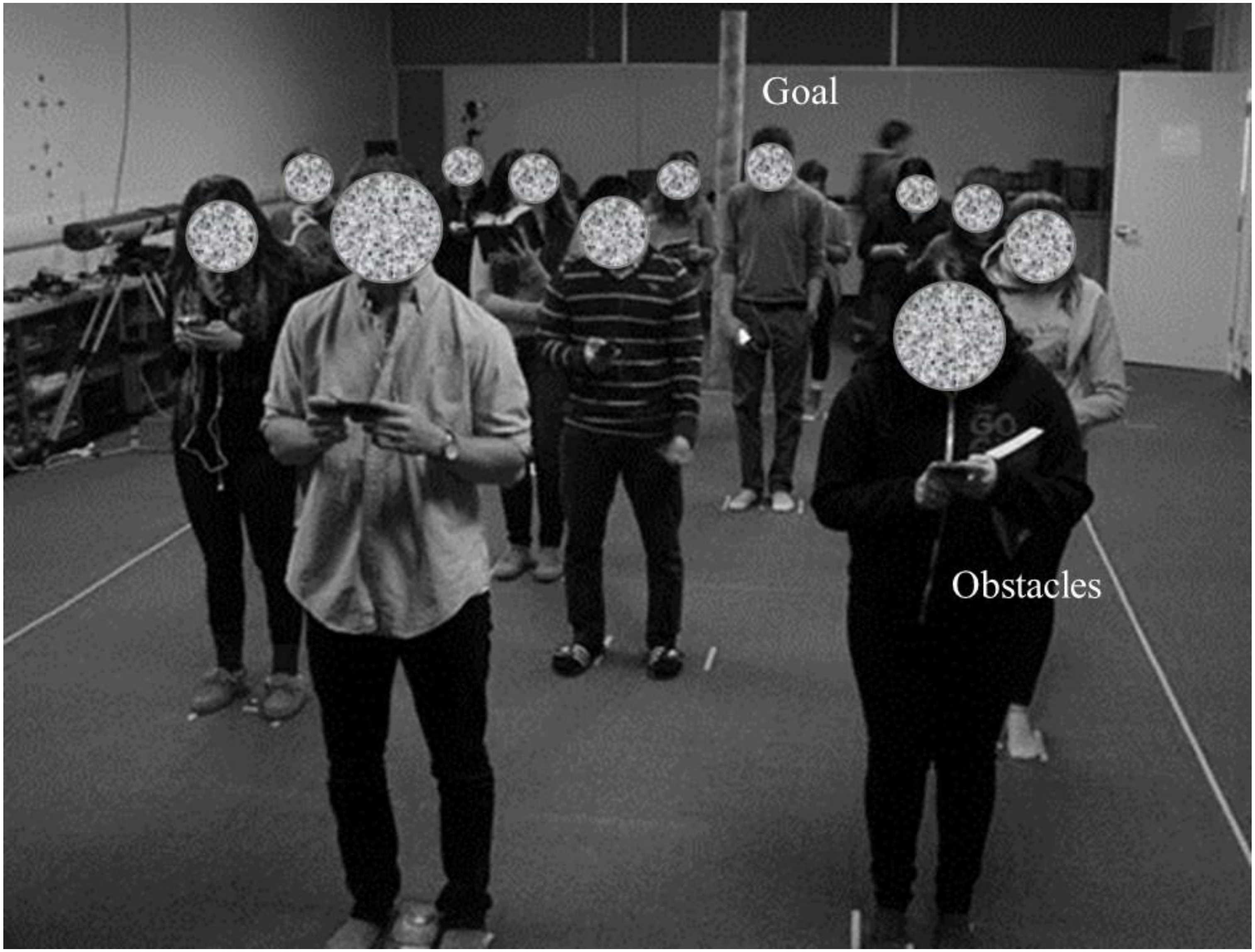
APPENDIX D – The Social Domain of the DOSPERT Questionnaire

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

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

1. Admitting that your tastes are different from those of a friend. ____________
2. Drinking heavily at a social function. ____________
3. Disagreeing with an authority figure on a major issue. ____________
4. Choosing a career that you truly enjoy over a more secure one. ____________
5. Speaking your mind about an unpopular issue in a meeting at work. ____________
6. Walking home alone at night in an unsafe area of town. ____________
7. Moving to a city far away from your extended family. ____________
8. Starting a new career in your mid-thirties. ____________
9. Staring a conversation with a group of strangers. ____________
10. Approaching a stranger to ask for directions. ____________

APPENDIX E – Crowded Room Experimental Setup


Goal
Obstacles

Supplementary Material

ARE POLES AND AVATARS TREATED DIFFERENTLY DURING APERTURE CROSSING IN VIRTUAL ENVIRONMENTS?

S.1 Abstract

The current study aimed to determine if the *critical point* when walking through apertures created by virtual pole obstacles is similar to that reported for real-world aperture crossing and to identify whether participants act differently when crossing apertures created by virtual pole obstacles compared to avatars. Eleven healthy YA wore a head-mounted-display (HMD), walked along a 10m path and passed through a virtual aperture located 5m from the starting location. Participants were instructed to avoid colliding with the obstacles when passing through the aperture. The experiment was conducted using a block design, where the aperture was either created by two pole obstacles or by two avatars. In both conditions, the width of the aperture ranged between 1.0 – 1.8x SW. Results revealed no clear drop in the *magnitude of shoulder rotations* as the aperture size increased for either type of aperture, which prevented a true *critical point* from being identified. Furthermore, individuals treated virtual poles and avatars similarly, as evident by the fact that no significant differences in the *magnitude* or *onset of shoulder rotations* produced at TOC and no differences in *walking speed* during the approach or at TOC. In real-world environments, aperture crossing behaviours are much different when walking between pole obstacles compared to human obstacles. The lack of difference between virtual poles and avatars in the current study may be due to a lack of social factors expressed by the avatars and as such, participants may have treated the avatars as any ordinary obstacles. Furthermore, the fact that no true *critical point* could be obtained for either obstacle type suggests that participants may have had difficulty accurately relating the size of their body (which they could not see) to the size of the aperture in the virtual environment and as such, could not accurately identify the affordance of aperture crossing.

S.2 Introduction

For ground-level walking it is well established that the *critical point* of aperture crossing is 1.3x SW: shoulder rotations occur for spaces 1.3x SW and smaller but not for spaces larger than this value (Hackney & Cinelli, 2013; Hackney, Vallis & Cinelli, 2013; Hackney, Cinelli & Frank, 2014; Hackney, Cinelli, Denomme & Frank, 2015; Warren & Whang, 1987; Wilmut & Barnett, 2010). Recent experiments have moved towards understanding aperture crossing behaviour for human interactions, where individuals are required to pass through narrow spaces created by other people and suggests that much larger spaces are required before an individual will pass through the aperture without producing a shoulder rotation. Specifically, individuals maintained a larger *critical point* (1.7 vs 1.3 for poles), initiated shoulder rotations earlier, rotated to a larger degree, left a wider *spatial margin*, and walked slower when approaching and passing through the human obstacles compared to poles (Hackney et al., 2015). Experimentally however, studying these human-human interactions is challenging and poses problems for the reliability of the experimental manipulations.

Virtual reality has become a popular method for studying human-human interactions during obstacle avoidance as it provides greater control over the experimental manipulations (Bruneau, Olivier & Pettre, 2015; Tarr & Warren, 2002). A number of studies have demonstrated similarities between general obstacle avoidance behaviours employed in real and virtual environments. For example, during single obstacle circumvention both the size and shape of the personal space envelope (Gerin-Lajoie, Richards, Fung & McFadyen, 2008) as well as the curvature of the locomotor path (Fink, Foo & Warren, 2007) are similar when circumventing obstacles in real and virtual environments. During aperture crossing tasks, when individuals are asked whether an aperture requires a shoulder rotation, similar-sized apertures are judged as passable regardless of whether they are real or virtual (Geuss, Stefanucci, Creem-Regehr & Thompson, 2010). Furthermore, when asked to walk through the aperture, individuals rotate their shoulders for similar-sized apertures in real and virtual environments (i.e., they have the same *critical point*) (Lepecq, Bringoux, Pergandi, Coyle & Mestre, 2009). In general, the results from the above-mentioned studies suggest that obstacle avoidance behaviours in virtual environments are comparable to those observed in real-world.

The purpose of the current study was two-fold: (1) to identify whether participants treat apertures created by avatars differently than virtual pole obstacles, and (2) determine if the *critical point* when walking in virtual reality is in line with previously reported real-world values (Chapter 4; Hackney et al., 2015). It was hypothesized that individuals would maintain a similar *critical point* for virtual pole obstacles as they do for real-world aperture crossing, but that avatars would be treated with increased caution compared to the pole obstacles.

S.3 Methods

S.3.1 Participants

Eleven YA ($\bar{x}_{\text{age}}$ = 20.7 ± 2.4 years) were included in the study and were free of deficits/disorders affecting their balance and decision making; had normal vision and did not knowingly experience motion sickness. After providing informed consent, the experimenters recorded the shoulder width of each participant using a measuring tape.

S.3.2 Apparatus and Procedure

The experiment was conducted in a 12m L x 12m W open space and participants wore a Rockwell Collins HMD. Head and trunk position was recorded by a hybrid inertial-ultrasonic tracking system (Intersense, Billerica, MA) through a sensor placed on posterior aspect of the HMD and on the posterior side of the right scapula.

The virtual environment consisted of a greyscale ground plane and black opaque walls. A red “home” pole appeared at the starting location and a second, red “target” pole appeared 10m away. On half the trials, two green pole obstacles appeared side-by-side, 5m from the starting location. In the other half of the trials, two female avatars appeared in place of the pole obstacles (Figure S.1). The poles and the avatars were presented in a blocked design which was counterbalanced between participants. Within each block, the aperture ranged from 1.0 – 1.8x SW in randomized order.

Participants were instructed to walk at their natural pace towards the red “target” pole and pass through the aperture without colliding with it. Once the participant reached the target pole, he or she stopped and turned around to face another target pole 10m away. At this time, the next trial began.

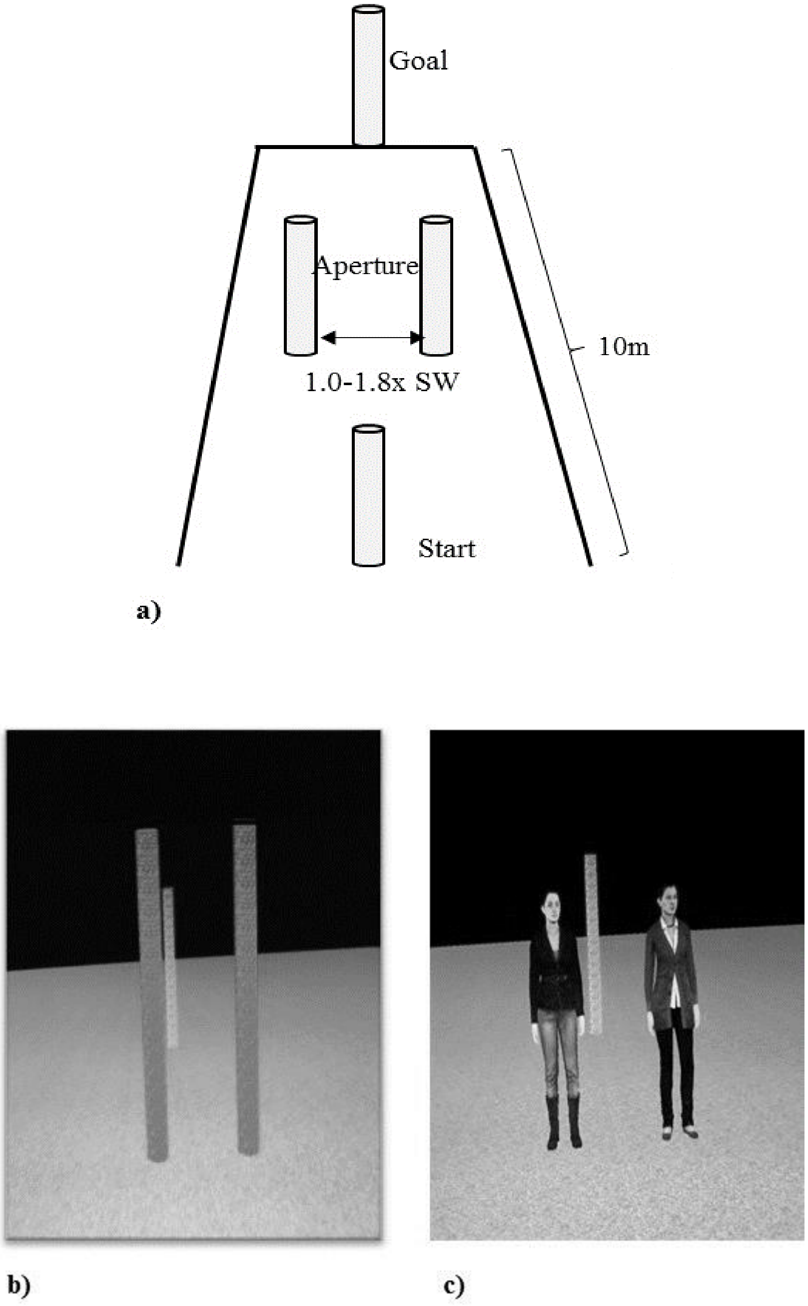


Figure S.1 – Experimental set-up including **a)** top-down view of the path, **b)** visual display for the virtual pole obstacles, and **c)** visual display for the avatar condition.

S.3.3 Data and Statistical Analysis

The *magnitude of rotation*, *critical point*, *onset of rotation*, *spatial margin,* and *approach velocity at TOC* were calculated in a similar manner as outlined in Chapter 2 and 3. Appendix A provides a visual representation of the dependent variables analyzed in this study.

A 2 (obstacle type: pole vs avatar) x 9 (aperture width) GLM with repeated measures was conducted for all dependent variables. A significant main effect of obstacle type or an interaction would indicate differences in behaviour between the virtual poles and avatars. *P*-values less than 0.05 were considered significant.

S.4 Results

Analysis of the *magnitude of rotation* revealed a main effect of aperture width ($F_{(8, 72)} = 35.07$, $p<0.01$, $\eta^2 = 0.49$), where rotations decreased as the aperture width increased. Post-hoc analysis revealed that rotation angle at apertures 1.0 - 1.4 were significantly greater than 1.5 - 1.8 ($p<0.05$ for all comparisons) (Figure S.2). However all aperture widths elicited rotations that were significantly greater than that of basic walking, suggesting that participants continued to rotate their shoulders at the largest aperture widths. Since there was no clear drop off in rotation magnitudes, a true *critical point* could not be identified. There was no significant effect of obstacle type or interaction.

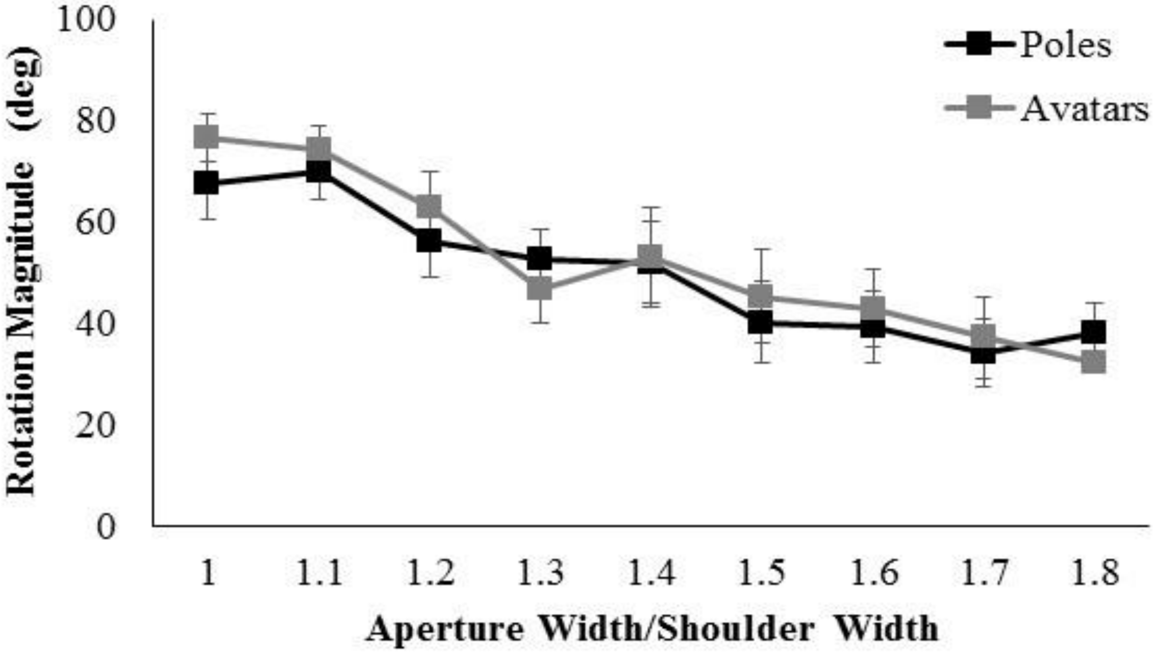


Figure S.2 – *Rotation magnitude* at each of the aperture widths. There was no significant difference between pole obstacles and avatars and no clear drop in rotation as the aperture width increased.

The 2 (obstacle type) x 9 (aperture width) GLM with repeated measures revealed no significant main effect of obstacle type or aperture width for the *onset of shoulder rotation*, *spatial margin, approach velocity* and *velocity at TOC.* The means and standard deviations of each variable for the two obstacle types are presented in Table S.1.

Table S.1 - Results for the dependent measures including the average, standard deviation and p value for the comparison between conditions. Variables included *magnitude of rotation*, *approach velocity*, *velocity at TOC* and *spatial margin*.

Dependent Measure	Virtual Poles ($\bar{x}$/SD)	Avatars ($\bar{x}$/SD)	*p*-value
Rotation magnitude (deg)	44.15 ±10.21	46.45 ±13.15	0.27
Onset of rotation (m)	0.52 ±0.07	0.50 ±0.09	0.42
Approach velocity (m/s)	0.82 ±0.01	0.83 ±0.02	0.27
Velocity at TOC (m/s)	0.79 ±0.02	0.85 ±0.02	0.29
Spatial margin (cm)	12.14 ±4.51	13.71 ±3.18	0.18

S.5 Discussion

The purpose of the current study was two-fold: (1) to identify whether participants treat apertures created by avatars differently than virtual pole obstacles, and (2) determine if the *critical point* when walking in virtual reality is in line with previously reported real-world values (Chapter 4; Hackney et al., 2015). A number of research studies have reported a consistent *critical point* of 1.3x SW when walking through apertures made of pole obstacles (Hackney & Cinelli, 2013; Hackney et al., 2013; Hackney et al., 2014; Hackney et al., 2015; Warren & Whang, 1987; Wilmut & Barnett, 2010). Furthermore, recent work has suggested that the *critical point* for crossing apertures made of human obstacles is much larger, at 1.7x SW. Since previous work has demonstrated similarities in obstacle avoidance behaviours between real and virtual environments (Fink et al., 2007; Gerin-Lajoie et al., 2008; Lepecq et al., 2009), it was hypothesized that individuals would maintain a similar *critical point* for virtual pole obstacles as they do for real-world aperture crossing and that avatars would be treated with increased caution, following in line with previous real-world results.

Interestingly, the current study was unable to detect a true *critical point* in either the virtual pole or the avatar condition. Analysis of shoulder rotations at TOC revealed no clear drop in the *magnitude of rotations* as the aperture size increased: individuals rotated their shoulders to the same degree at the largest aperture as they did for the smallest (Figure S.2). In real-world environments, a clear drop in the *magnitude of rotation* is observed as the aperture size increases (Warren & Whang, 1987). Although Lepecq and colleagues (2009) established similar *critical points* between real and virtual environments, our results appear to contribute to the growing body of inconsistent findings. Similar to our findings, Stappers and colleagues (1999) also described difficulties distinguishing a *critical point*, as they too observed no clear drop off in rotations as aperture widths increased. The lack of a *critical point* may be explained by the fact that individuals were not able to view their own body in the virtual environment and therefore may have had difficulty accurately relating the size of the aperture to the size their body. As such, Fink and colleagues (2007) proposed that difficulty establishing eye height within a virtual environment, especially when the body cannot be viewed, may yields an ambiguous perceptual scales for establishing body-scaled actions. Since aperture crossing is largely body-scaled (Hackney et al., 2013; Hackney et al., 2014; Keizer et al., 2013; Warren & Whang, 1987), the fact that there was a lack of a *critical point* suggests that this body-scaled relationship was not established or was not established correctly.

Recent work has suggested that the inclusion of a self-avatar may help improve the examination of perception and action in a virtual reality environment. Mohler and colleagues (2010) found that individuals who explore near space while viewing a representation of their own body made more accurate distance judgements than those who had no visual reference. Similarly, Lin and colleagues (2012) demonstrated that the presence of a self-avatar improved the accuracy of stepping over and ducking under obstacles. Together, these studies suggest that providing a self-avatar can increase the similarities between virtual environments and the real world. Therefore, future aperture crossing tasks in virtual reality should consider including self-avatars to help individual’s establish body-scaled metrics and yield more accurate scaling of actions.

In addition to a lack of a true critical point, the results of the current study demonstrated no differences in aperture crossing behaviour between the virtual pole and avatar conditions. This result was unexpected, since previous research has observed that individuals act more cautiously in a real world environment when walking through human obstacles, by walking slower and maintaining a larger *critical point* and *spatial margin*. However, unlike human and real-pole obstacles, individuals in the current study behaved similarly for virtual poles and avatars (Table S.1). A substantial body of research has demonstrated that as long as the avatars exhibit behaviour that appropriately responds to the user's actions, a participant's interaction with the avatar will be similar to the way they interact with real people (Durlach & Slater, 2000; Slater et al., 2006; Zhang, Yu & Smith, 2006). Bailenson and colleagues (2002) argued that gaze direction is of particular importance for this effect. While the gaze of the avatars in the current study moved as the participant approached, it likely did not match what a real person would do in a similar scenario. Rather than looking directly at the oncoming pedestrian as would be expected in a real-world setting, the avatar's gaze slowly shifted from side to side. Furthermore, the avatars remained in a stationary position before, during and after the interaction with the participant even when the aperture was very small. This completely stationary response is not likely to be encountered in a real-world setting, as people typically act to keep others outside their own personal space boundary (Gerin-Lajoie et al., 2005). Therefore the behaviour of the avatars in the current study may have removed important human-like qualities from the experience, such as personal space boundaries and social factors, which have been suggested to elicit more cautious behaviours in a real-world setting (Hackney et al., 2015; Knowles et al., 1976). As a result, participants may have acted similarly for virtual poles and avatars simply because they projected similar qualities.

S.5 Conclusion

The findings of the current study are two-fold. First, the passability of apertures appears to be different in virtual reality than that reported in real-world settings. Aperture crossing in virtual reality appears to lack a true *critical point* which likely results from difficulty relating the size of the aperture to the size their body. Second, individuals perform similarly when walking through apertures created by virtual pole obstacles compared to avatars. This result is quite different than of real-world aperture crossing, where individuals act much more cautiously for human obstacles than they do for poles (Hackney et al., 2015). It is likely that individuals interacted similarly for the avatars as they did for the virtual poles because the avatars did not respond appropriately to the actions of the user. Future research should consider including a self-avatar to assist participants in establishing an accurate body-scaled metric to identify whether the aperture affords passage and avatars that possess more human-like qualities, such as appropriate gaze behaviour.

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